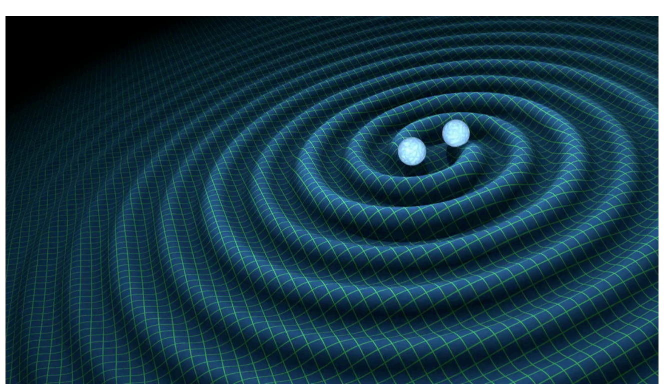
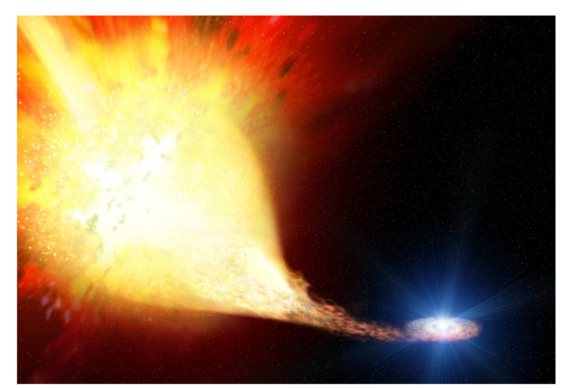
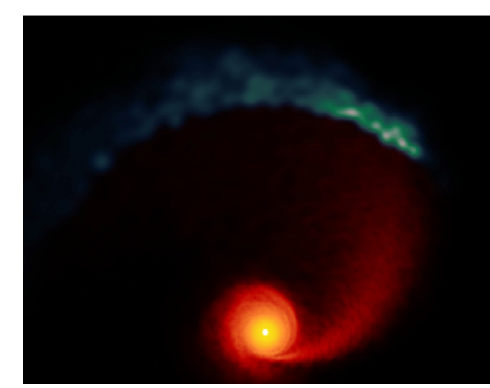
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

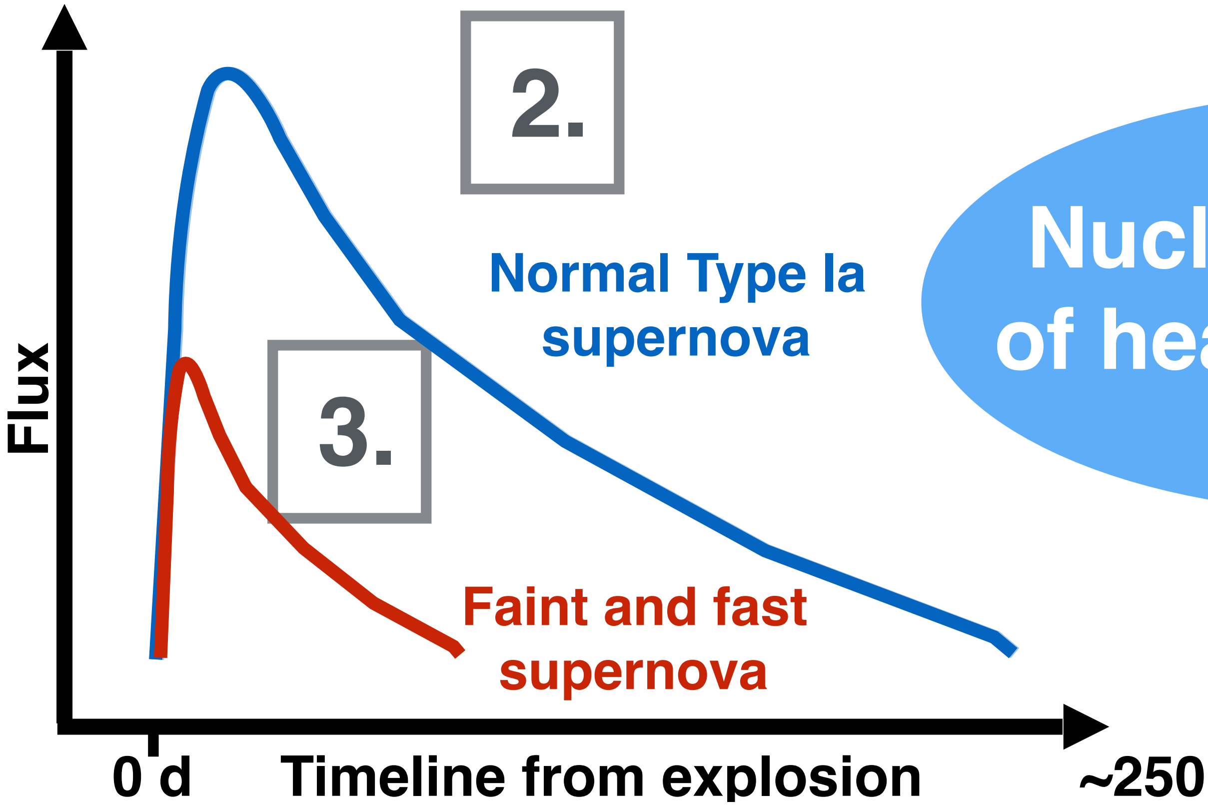
Explosive transients: Type Ia supernovae and white dwarf explosions

Kate Maguire (she/her)
Trinity College Dublin

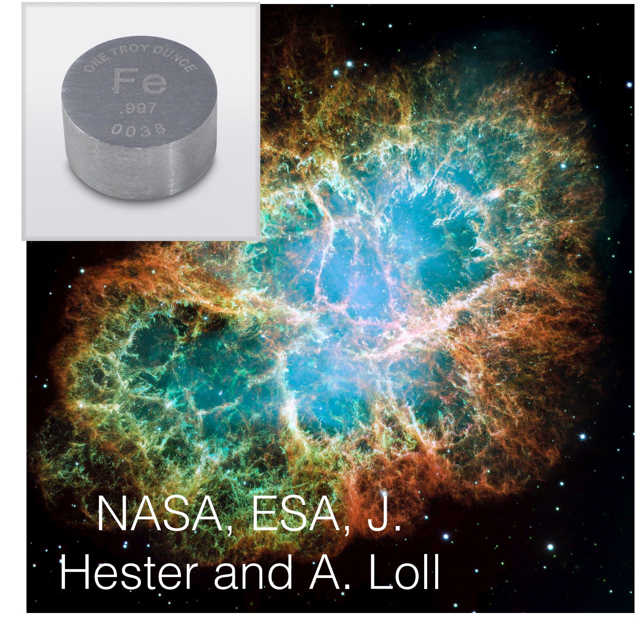




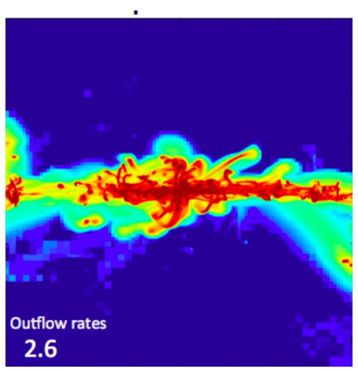




Nucleosynthesis of heavy elements



Impact of white dwarf explosions in the Universe



1.

Powering feedback dynamics

Cosmological constraints

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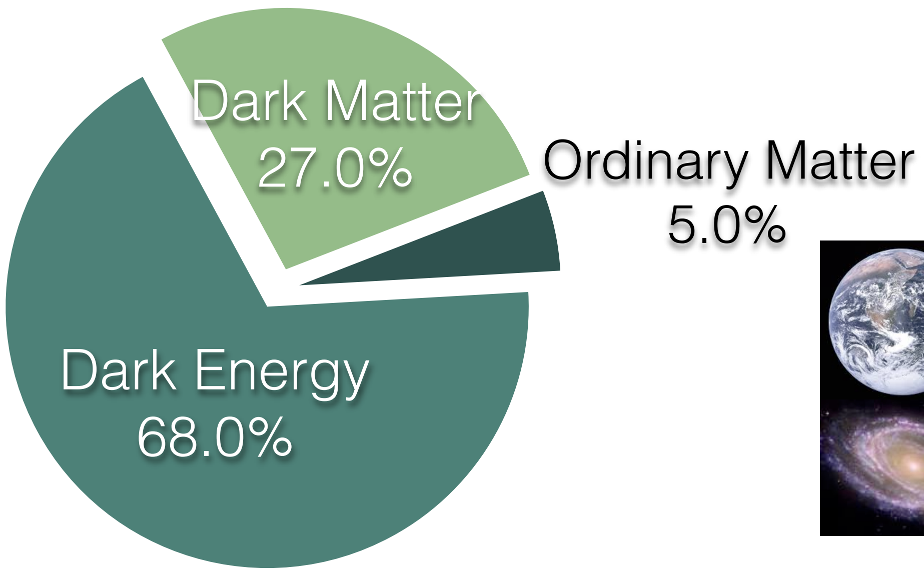
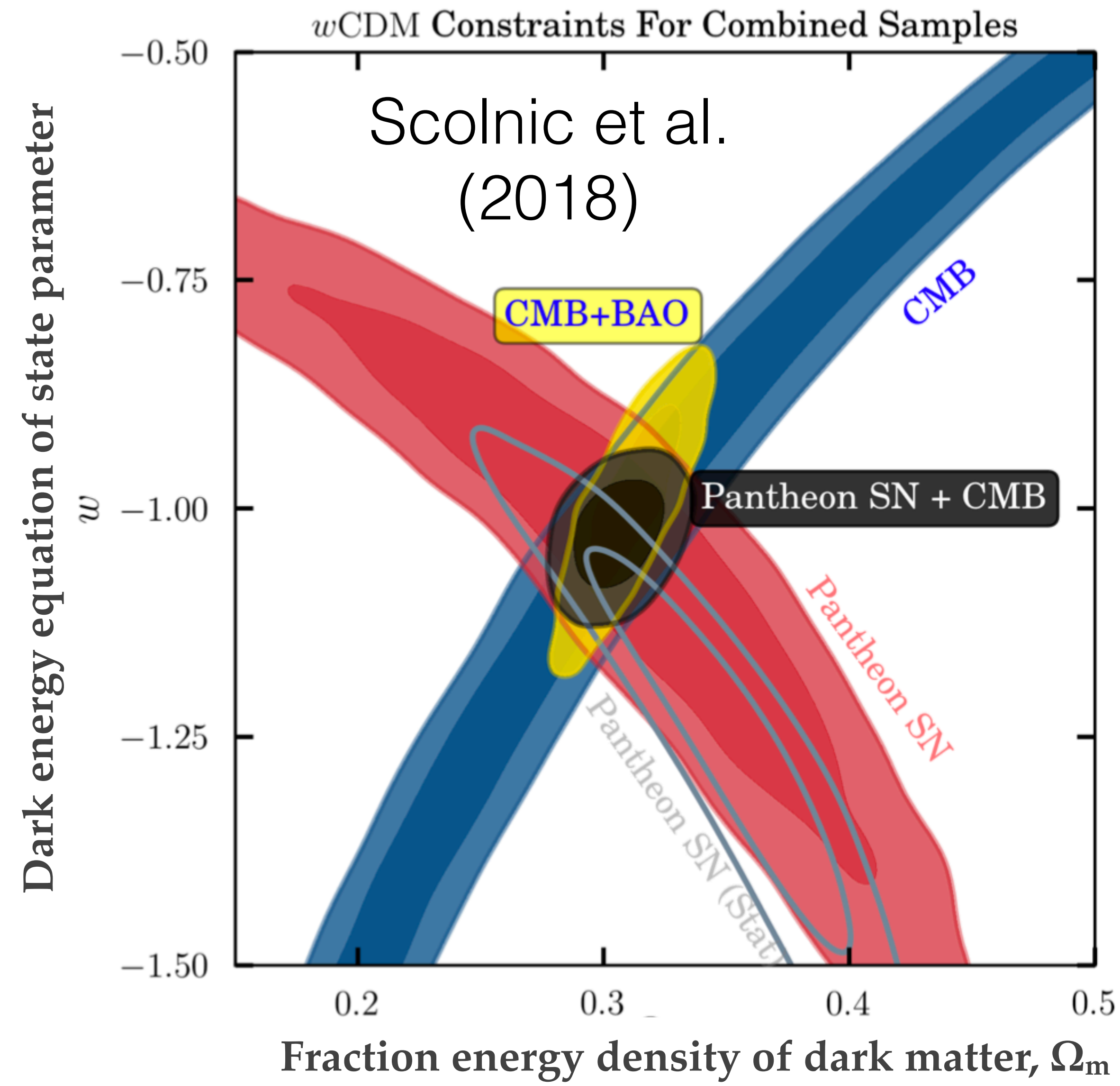
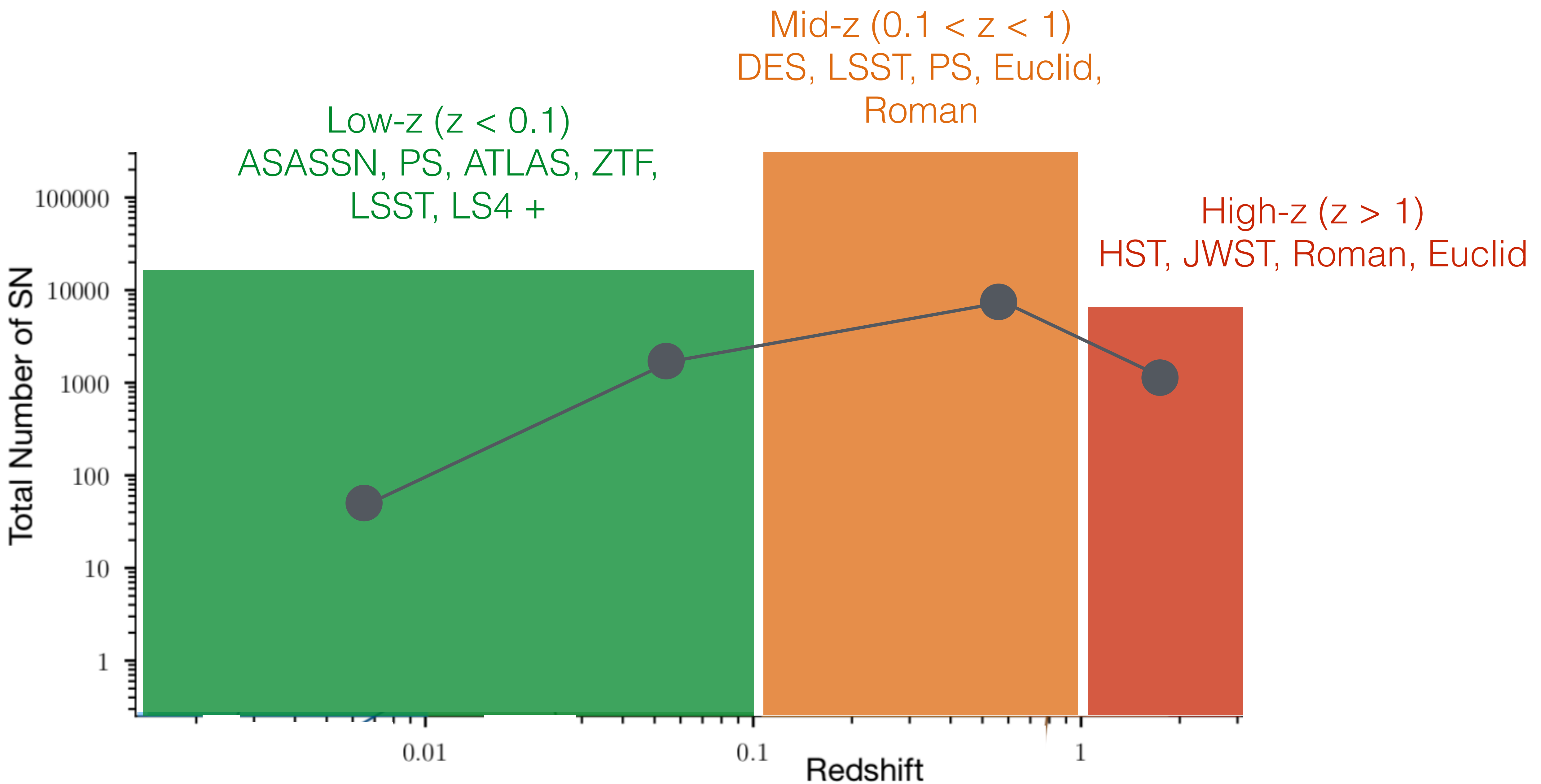
Type Ia supernovae cosmology results





- 'Pantheon' SN sample - 1000 SNe from $0.01 < z < 2.3$
- w consistent with -1 (Scolnic et al. 2018)
- Is w time varying?
- H_0 - investigating tension between the early and late Universe measurements

Type Ia SN discoveries in the next decade

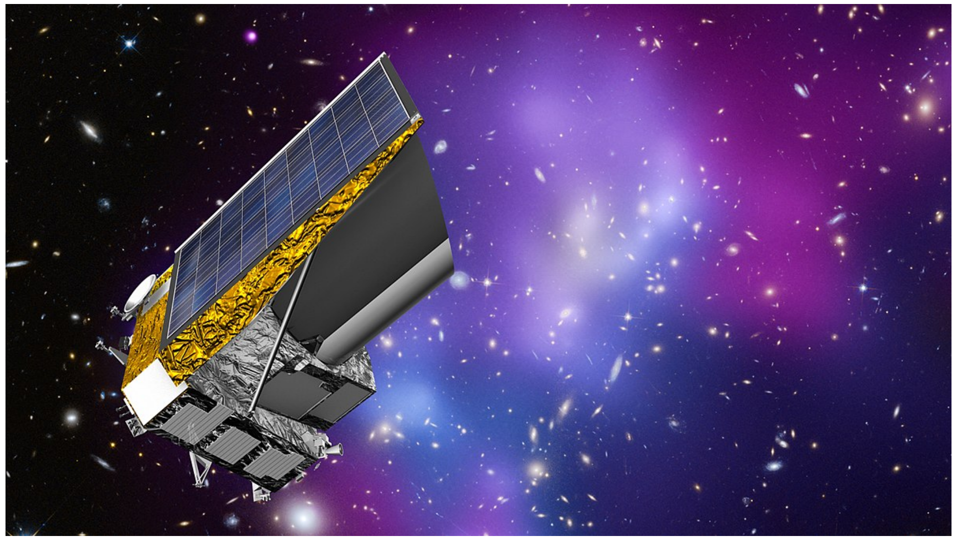


Boxes: Total anticipated discoveries across each redshift range
Points: Expected classifications with spec. follow-up (shown approx. at median z)

Adapted from Scolnic+ Astro 2020 white paper

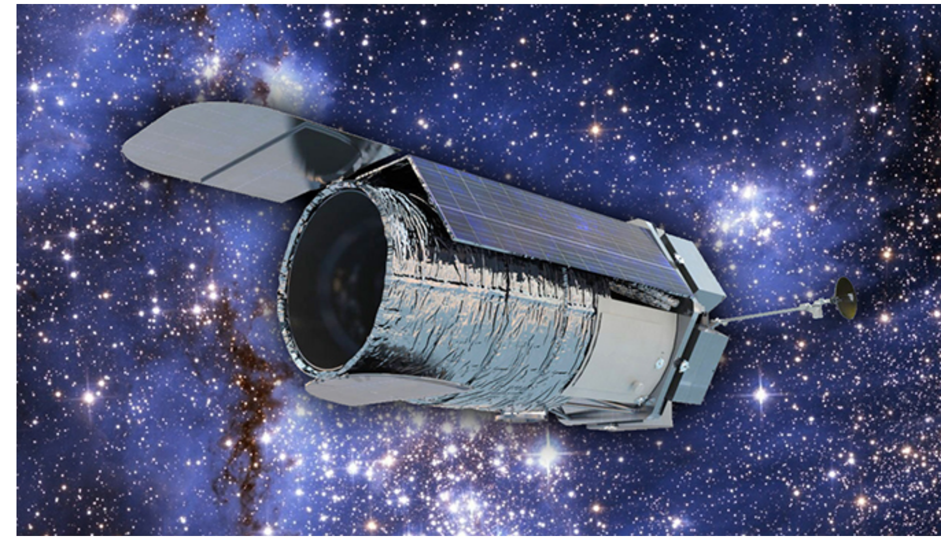
High-redshift Type Ia supernovae for cosmology

Euclid



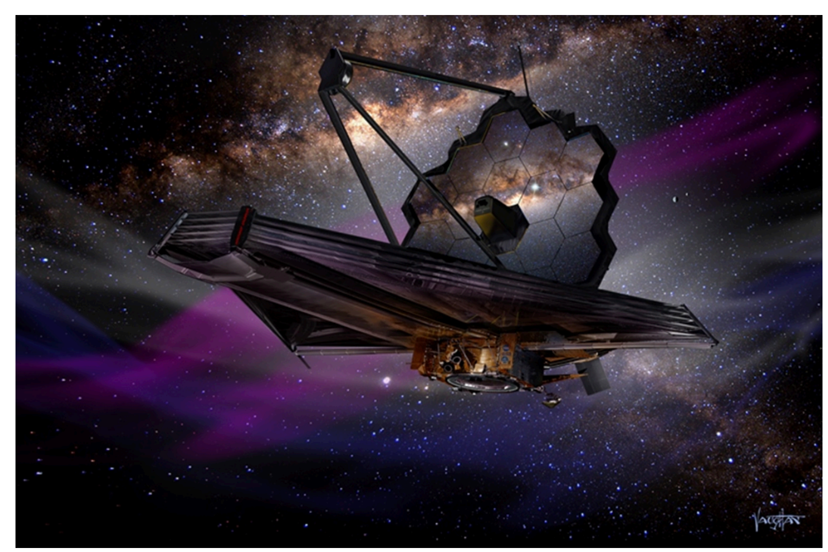
SN Ia DESIRE survey out to z~1.6 (Astier+ 2014)

Roman Space telescope



SNe Ia out to z~1.7 (Spergel+ 2015)

JWST



Potential for SNe Ia out to z ~ 5

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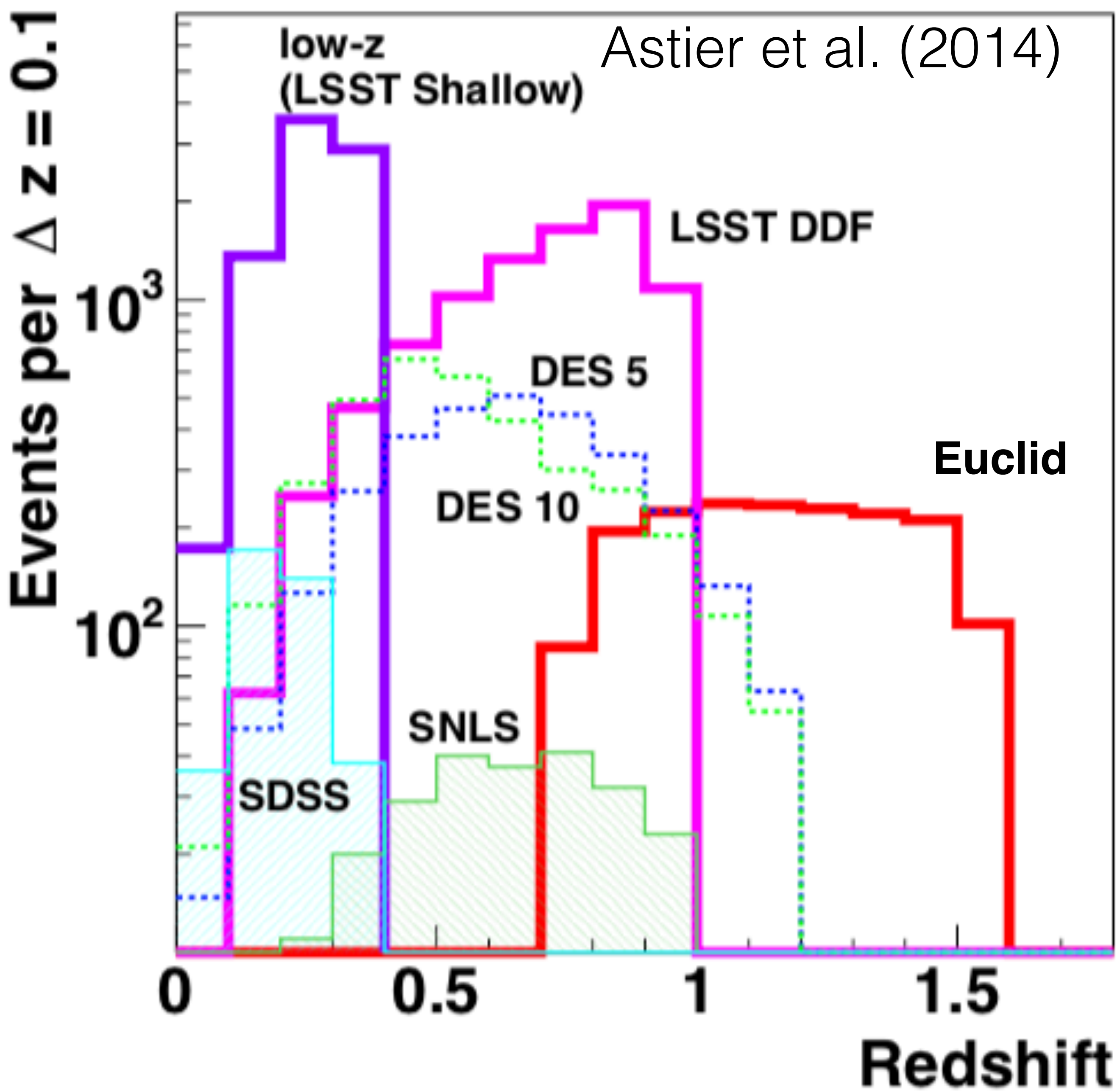
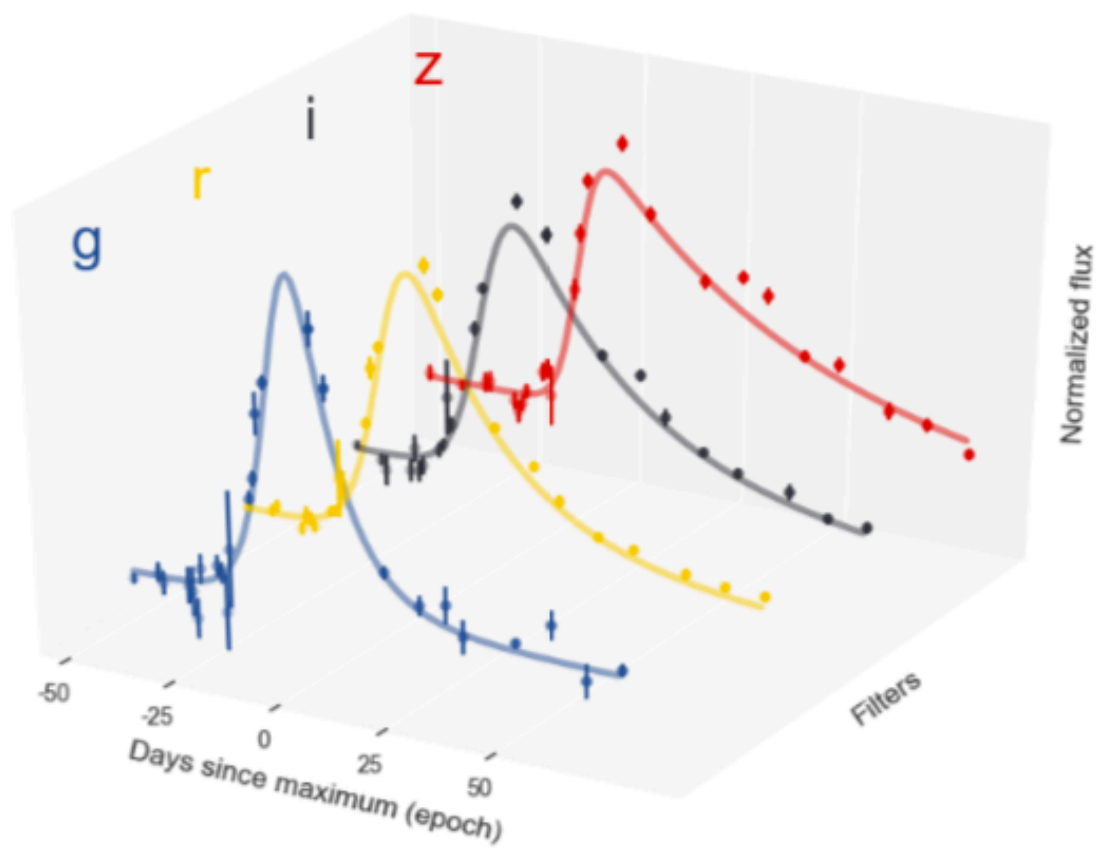
Space-based high redshift missions - Euclid + Roman



- **Euclid** SN Ia DESIRE survey - 1800 SNe in 6 months of telescope time
- Similar survey planned with **Roman** - High Latitude Time Domain Survey (HLTDS) + spectroscopy

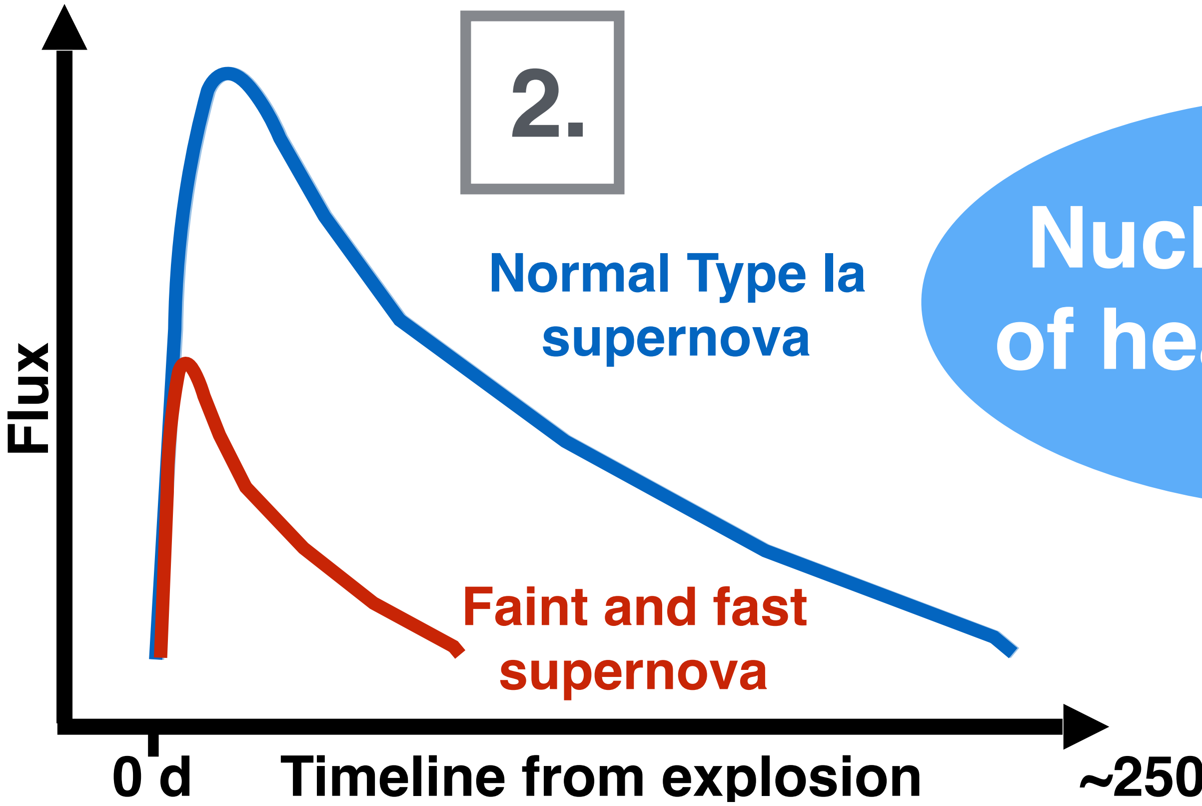
Type Ia supernova (and host) spectroscopy is essential

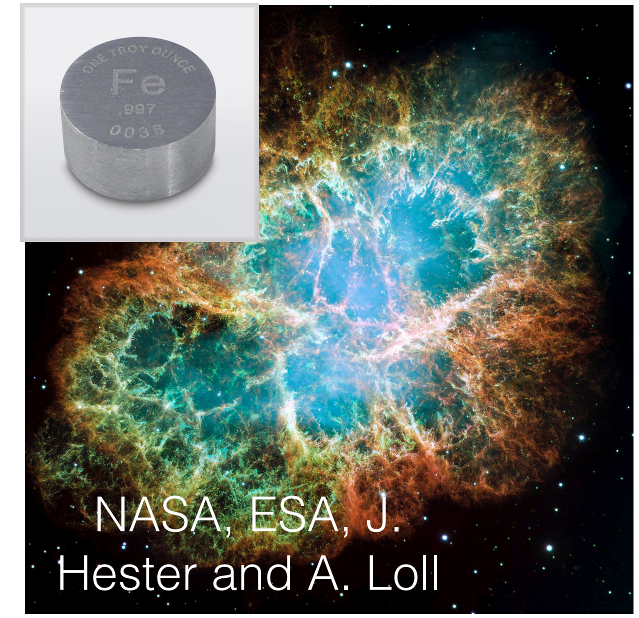
Ishida et al. (2018)



- Aiming for photometric classification for SN Ia cosmology samples
- **But spectroscopic validation samples still needed**
- ELTs for high-z events
- Multi-object spectrographs e.g. 4MOST

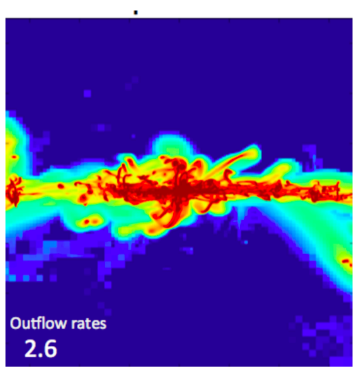
- Biggest limitations in future SN Ia cosmology
  - Calibration
  - Lack of knowledge of SN Ia physics, e.g. progenitor evolution with redshift, what exactly explodes





Nucleosynthesis of heavy elements

Impact of white dwarf explosions in the Universe



Powering feedback dynamics

Cosmological constraints

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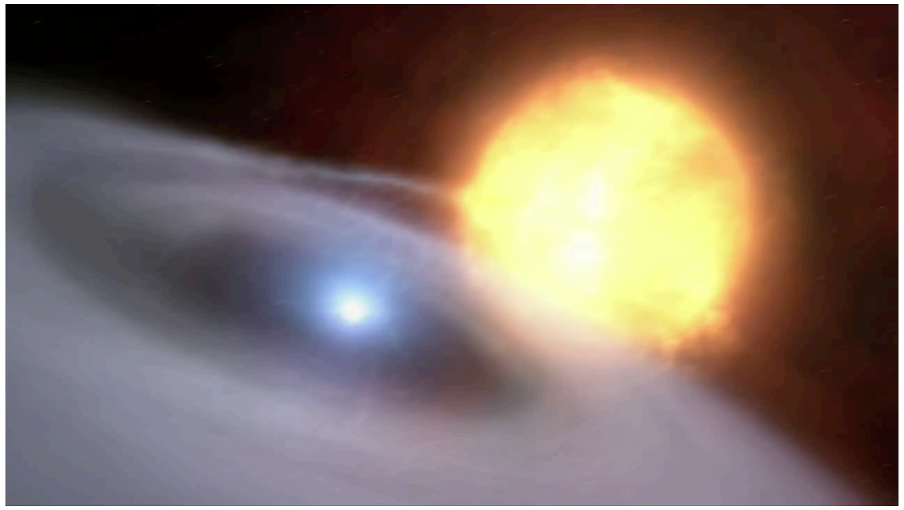
How do Type Ia supernovae explode?

Scenario 1

Single degenerate?



Red giant? Main-sequence star?

Scenario 2

Double degenerate?

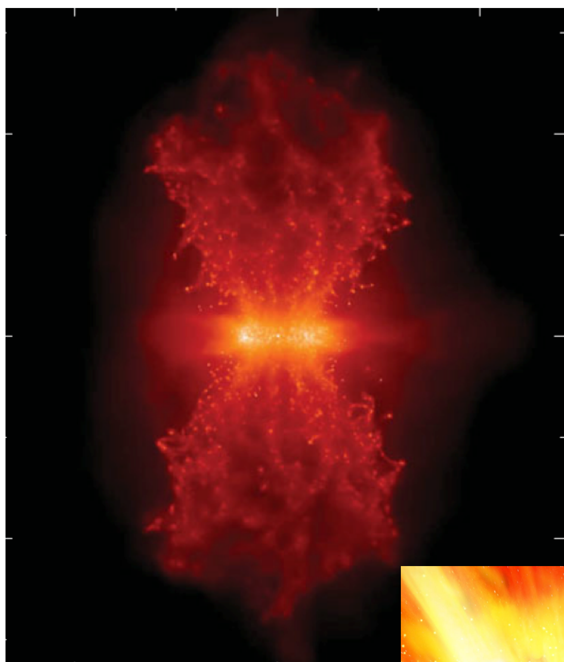
Another white dwarf?

- Progenitor system has never been directly detected
- Most likely both contribute to ‘normal’ SNe Ia
- Key question is relative rates

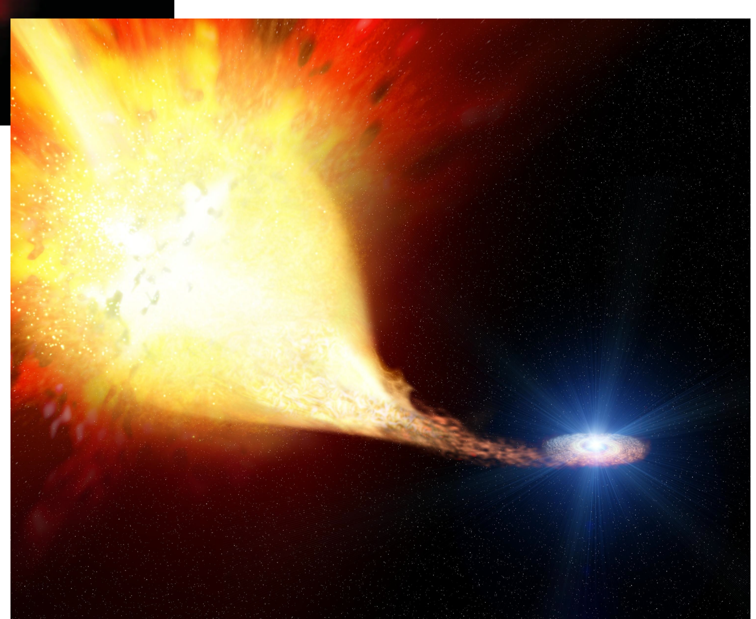
Two broad classes of explosion models

Explosion at ~$M_{chandra}$ (1.4 Msun)

M_{ch} (via winds)?

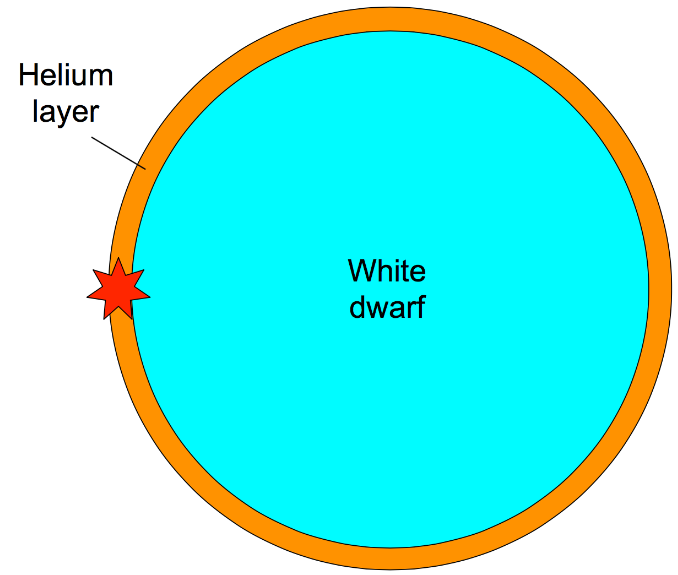


M_{ch} (via RLOF)?

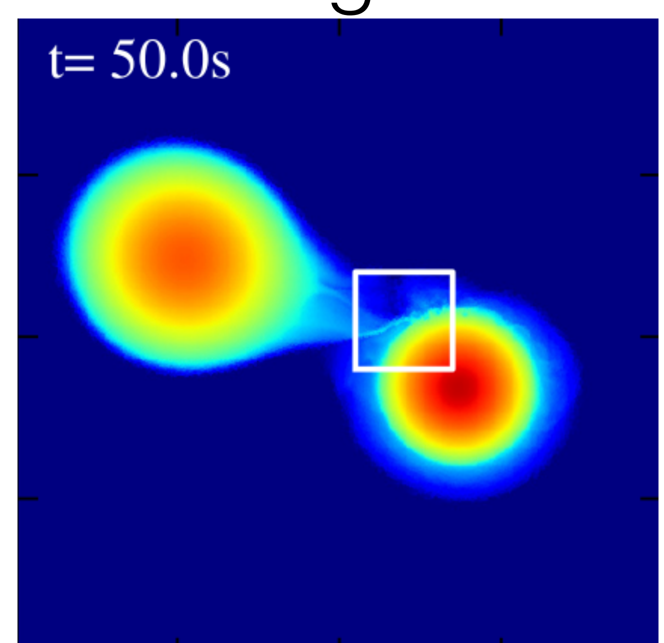


Explosion sub-$M_{chandra}$ (<1.4 Msun)

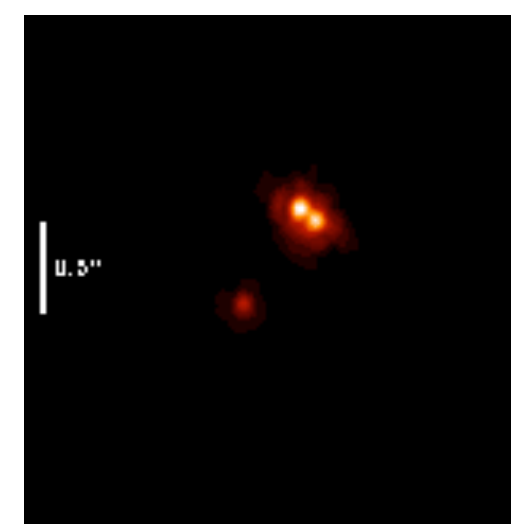
Double-detonation?



Merger?



Direct collisions?



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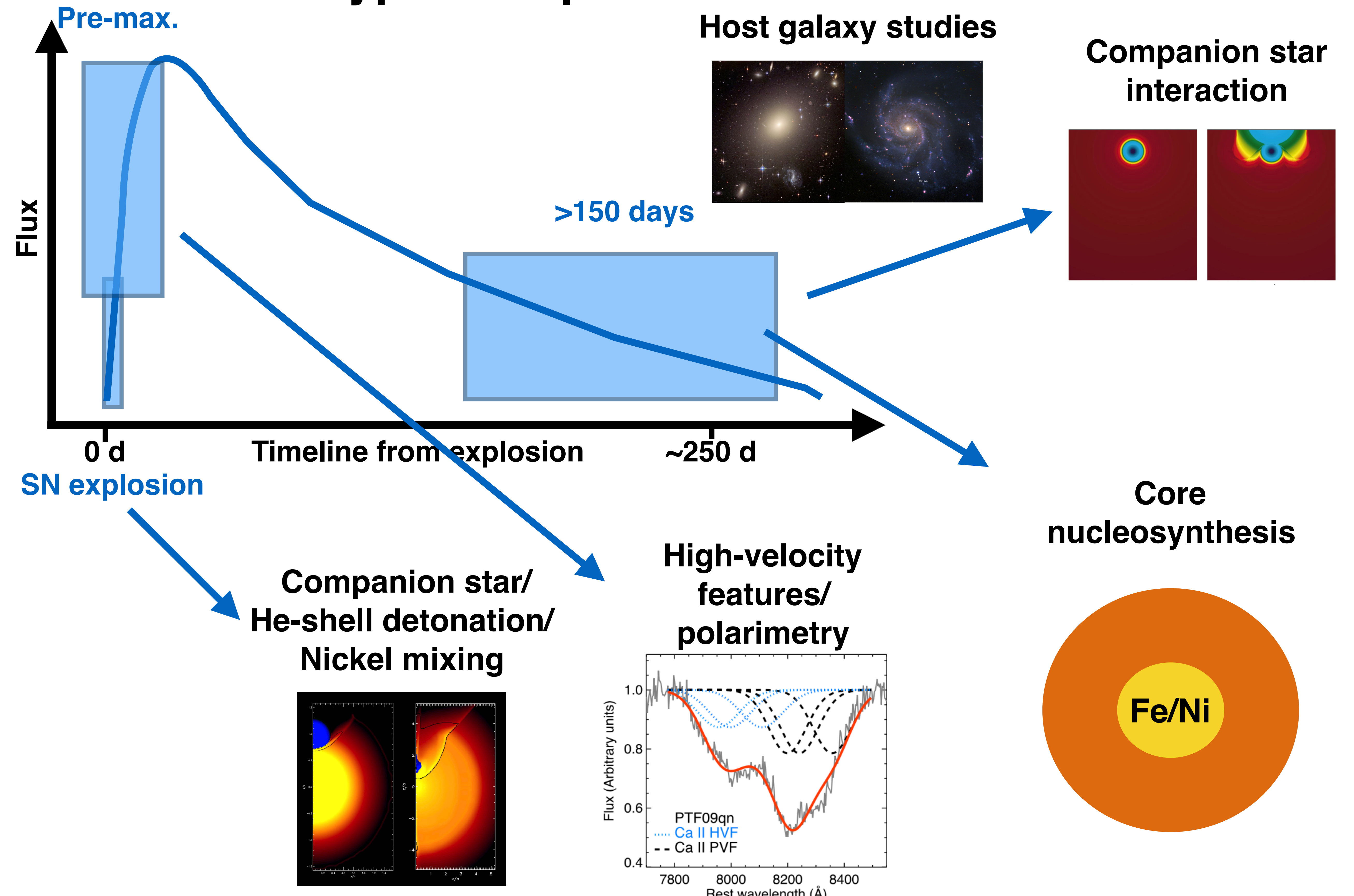
What observations can distinguish between explosion scenarios for Type Ia supernovae?



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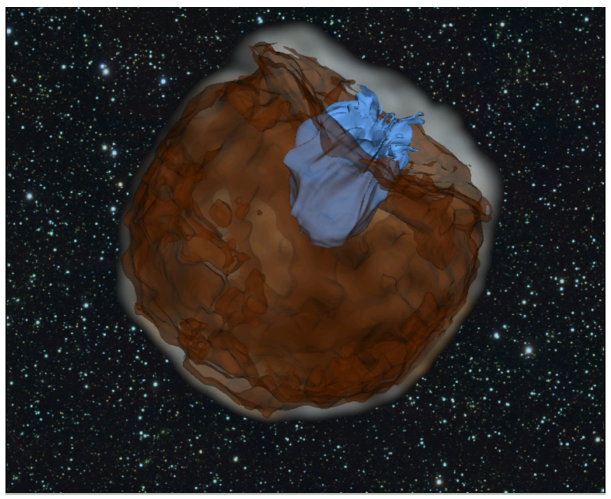
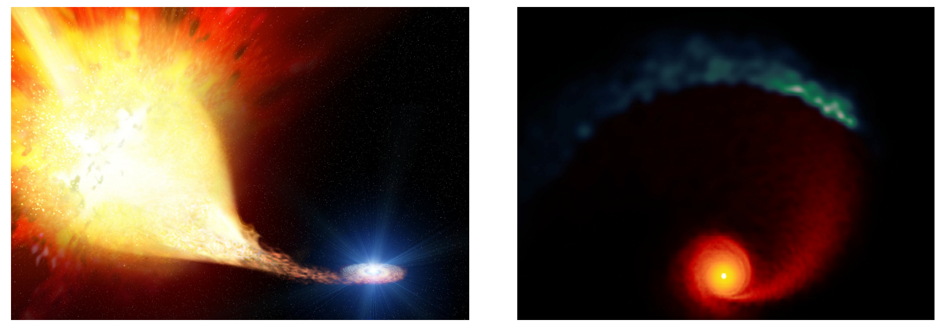
Why are early SN Ia light curves interesting?

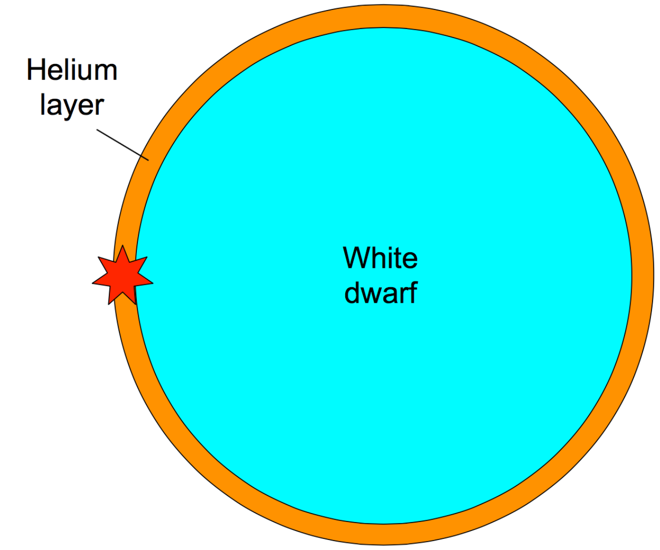
Ejecta - companion star interaction?



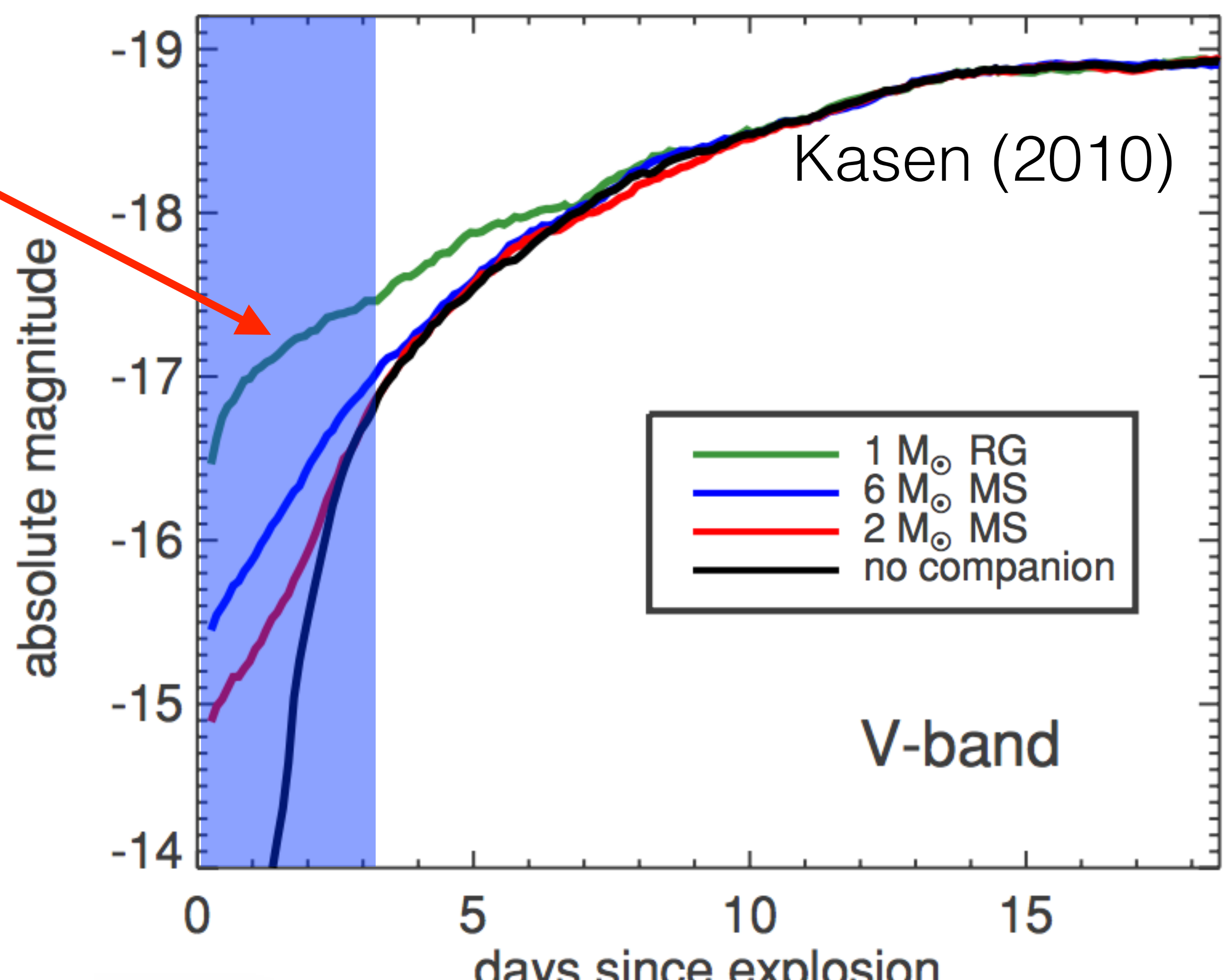
Ejecta mixing?
(Magee & Maguire 2020)



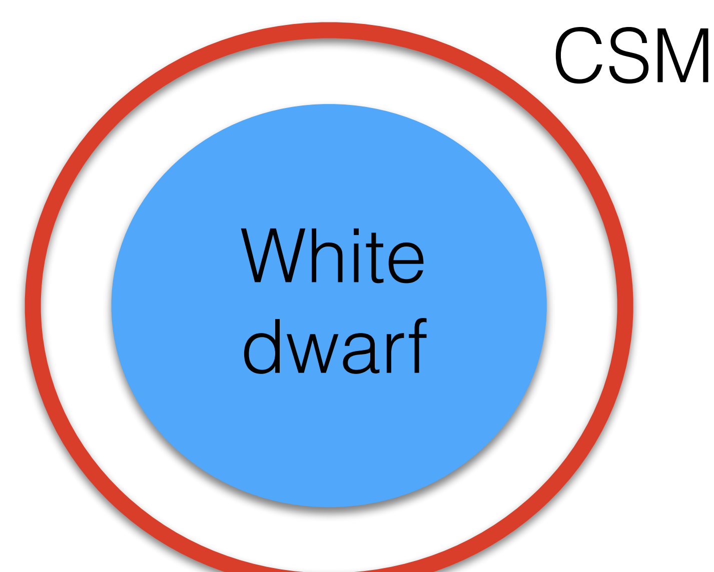
He-shell detonation?
(Noebauer+ 2017)



First days after explosion



Ejecta - CSM interaction?
(Piro & Morozova 2016)



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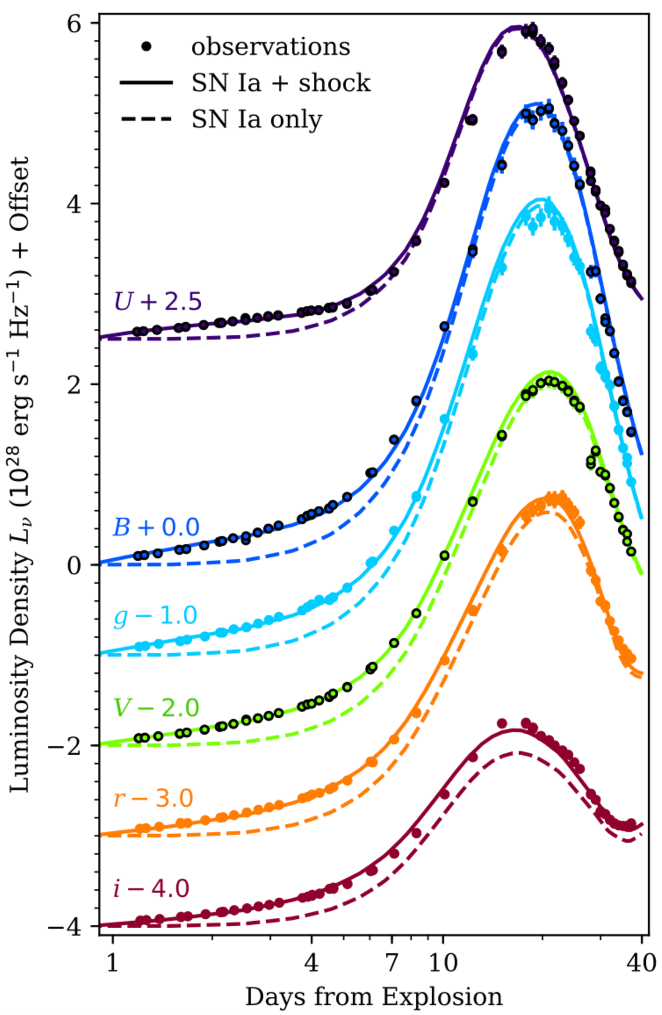
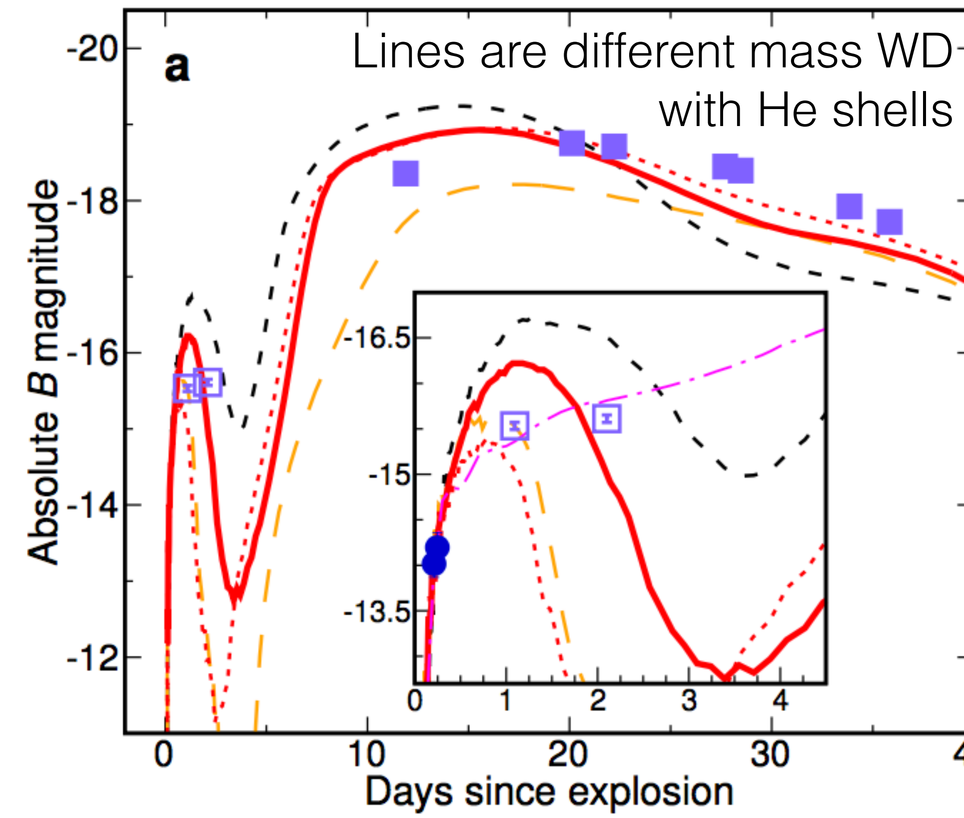
Early flux excesses identified in Type Ia supernovae

SN 2017cbv

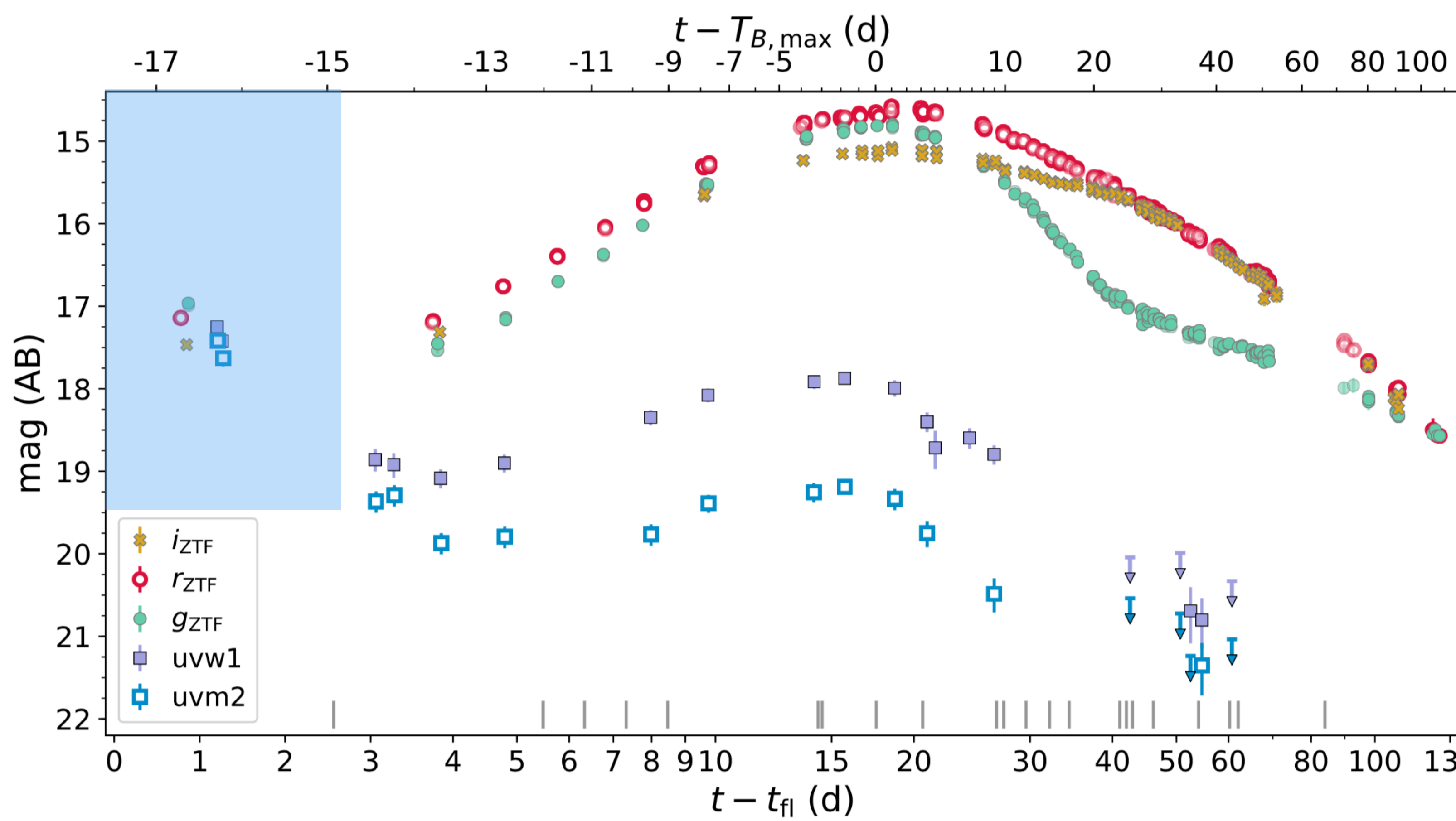


Hosseinzadeh et al. (2017)

MUSSES1604D Jiang et al. (2017)



Early UV flash
SN 2019yvq Miller+ 2020



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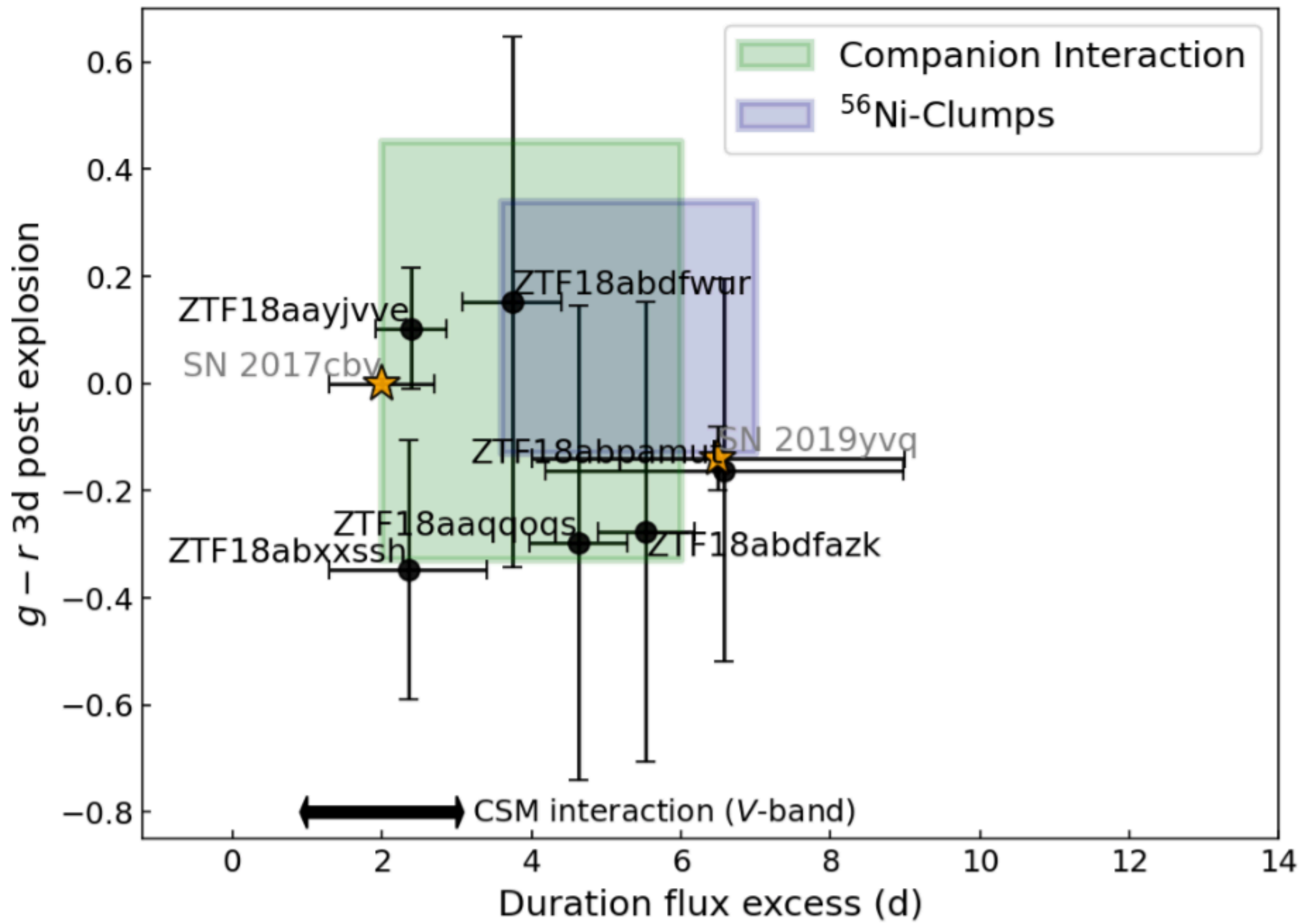
Properties of early flux excesses

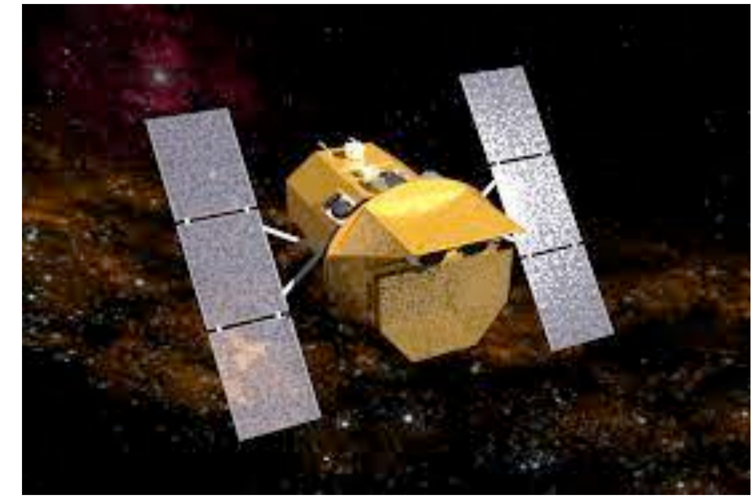
Deckers, KM,+ (2022)



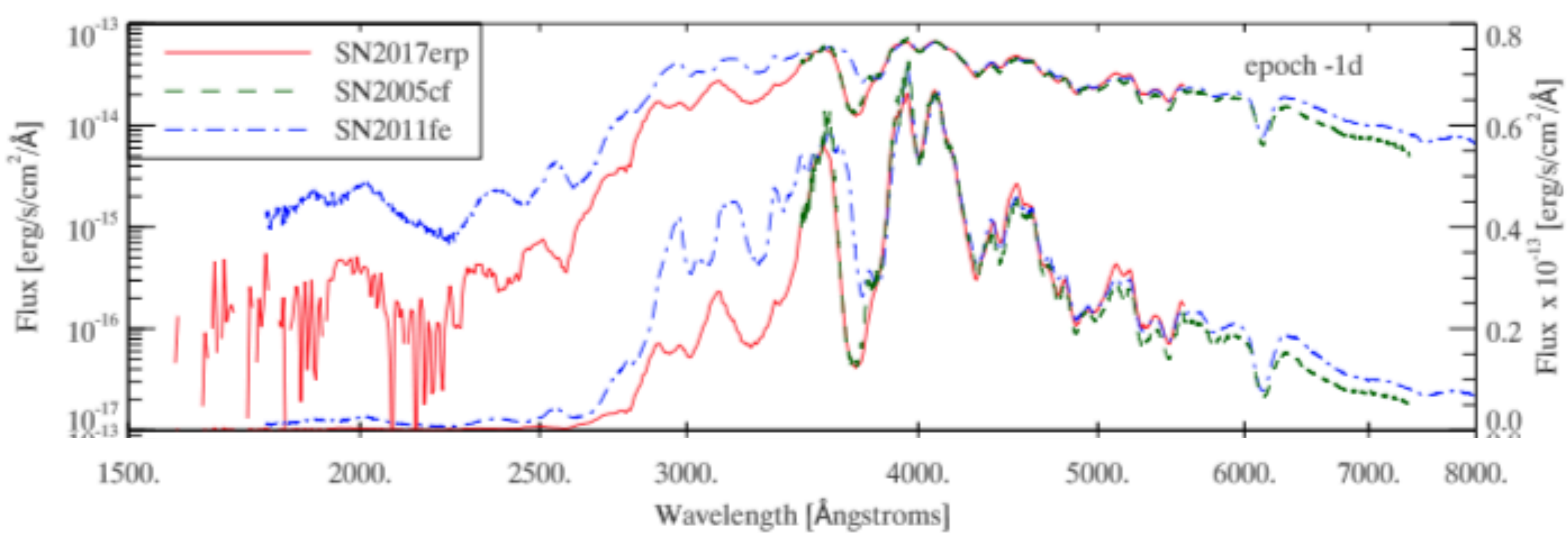
- ZTF sample of 115 SNe Ia - Intrinsic rate of ‘bumps’ of 18 +/- 11%
- Use time scales to determine link to explosion models

How do we identify the origins of flux excesses?

- Very early detection - high cadence ground based facilities
- Model are brightest in the UV
- **Neil Gehrels Swift** observatory - rapid UV imaging
- Phase A approved for **UVEX** - UV imaging survey + spectroscopy



- Early UV spectroscopy with HST (e.g. Brown et al. 2018) - probe diversity



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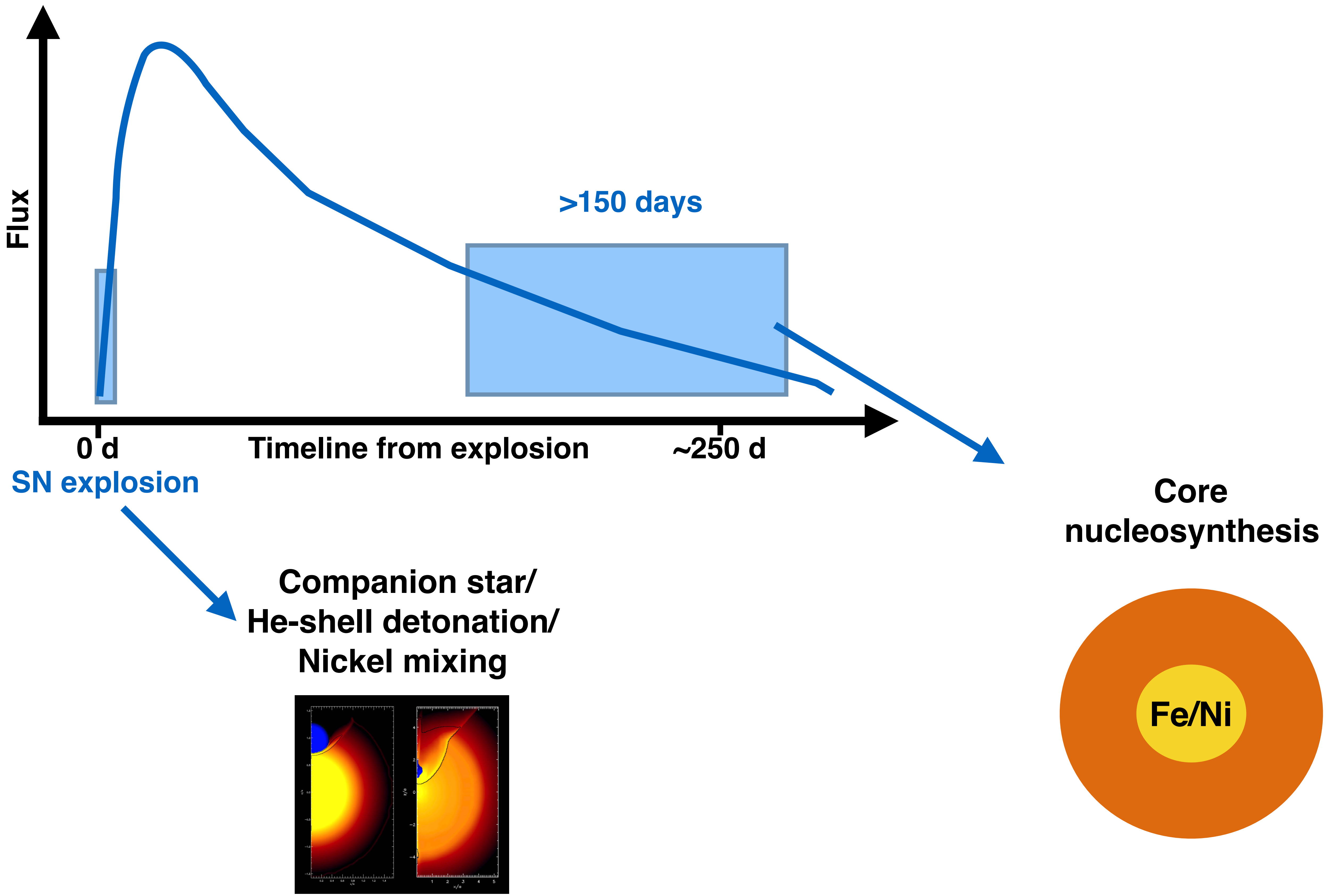
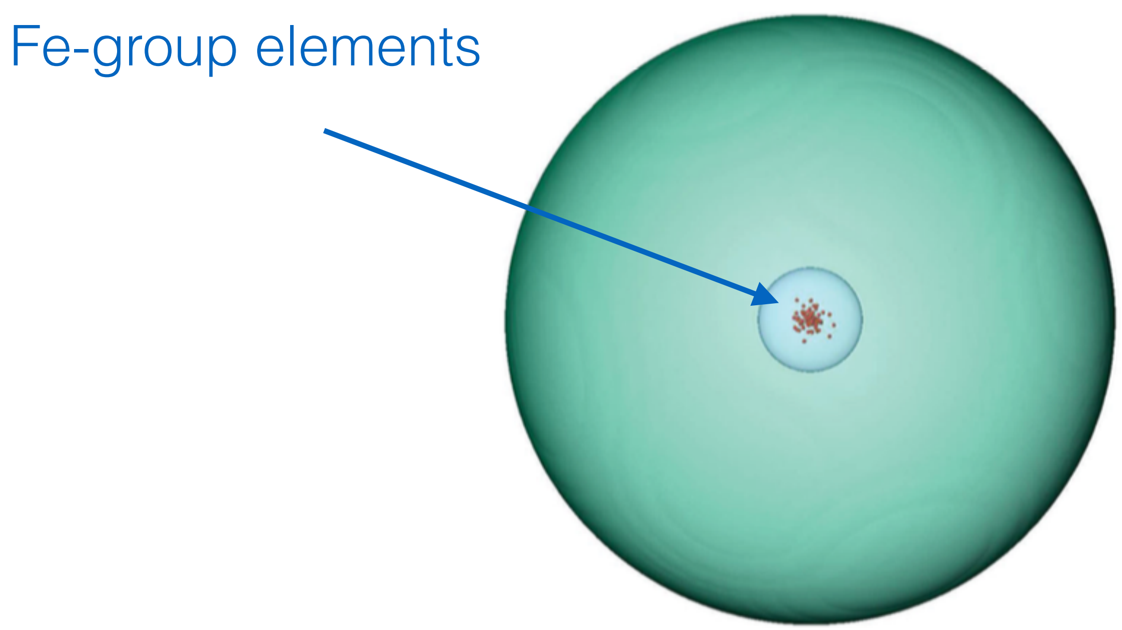
What observations can distinguish between explosion scenarios for Type Ia supernovae?



Studying nucleosynthesis with late-time spectroscopy

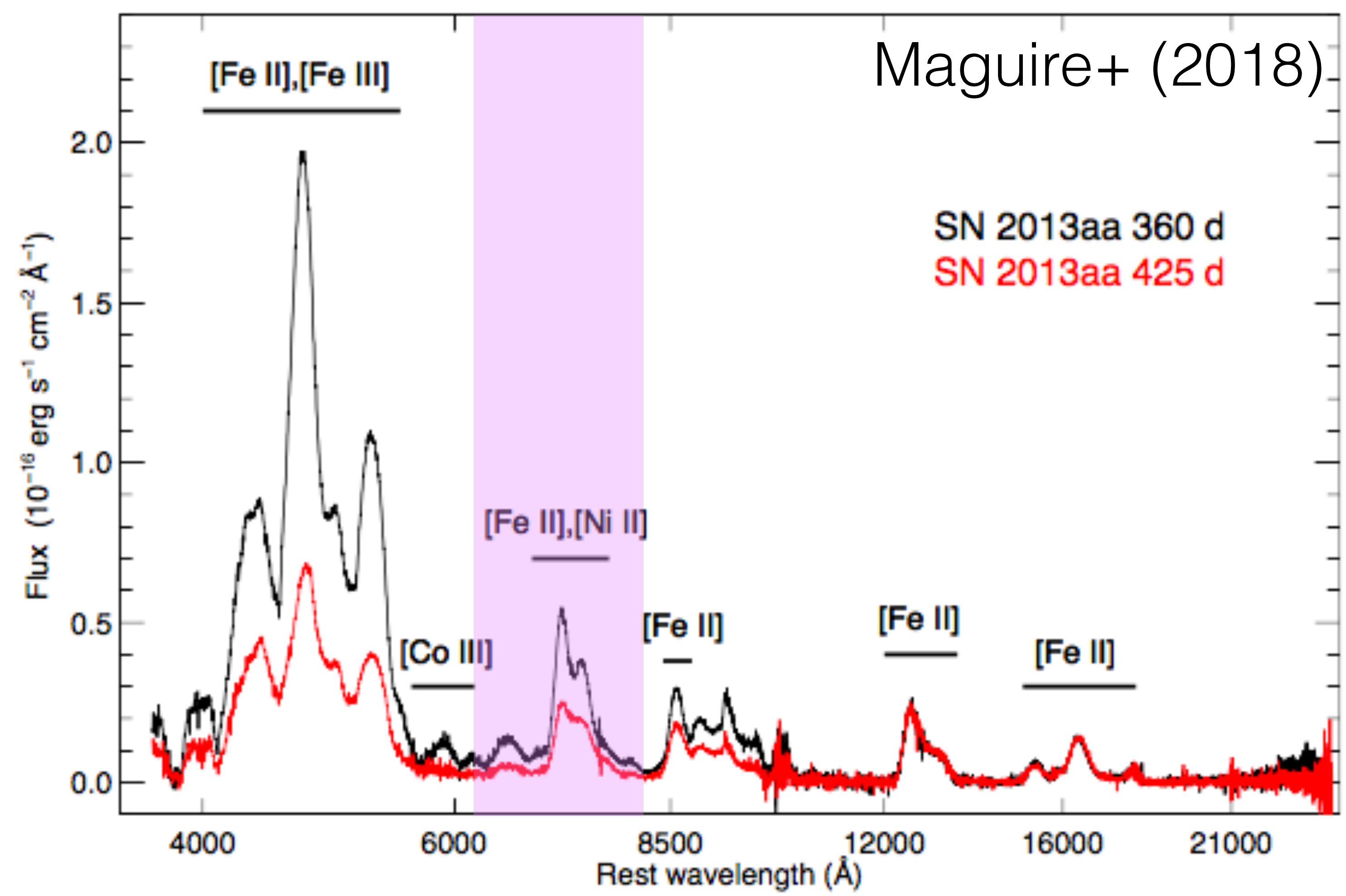


- Outer layers of ejecta become transparent with time

- Any Ni observed at late times is **stable Ni** and highly dependent on density of WD at time of explosion

$$^{56}Ni \rightarrow \ ^{56}Co \rightarrow \ ^{56}Fe$$

Half-life 6.1 d Half-life 77.3 d



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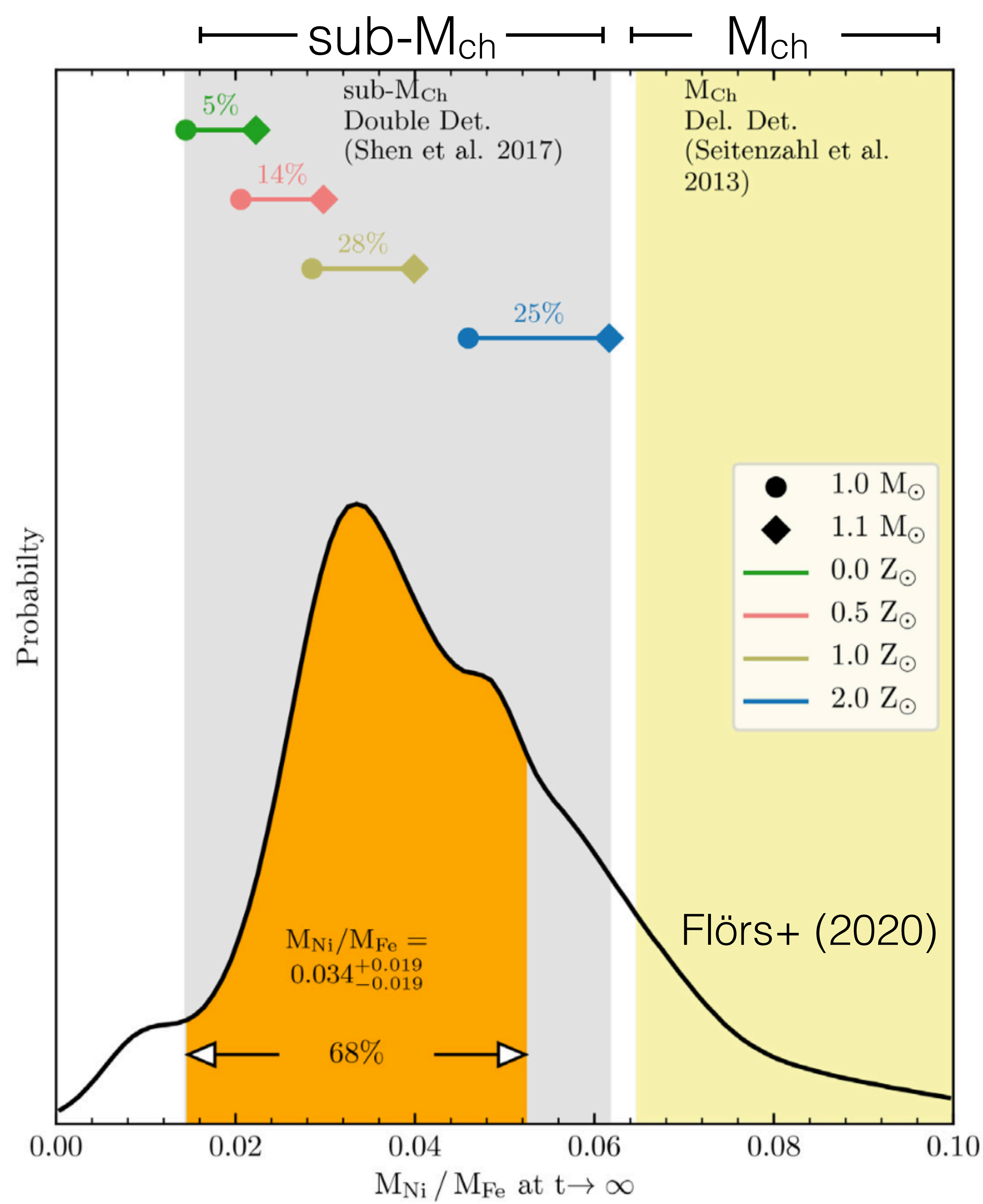
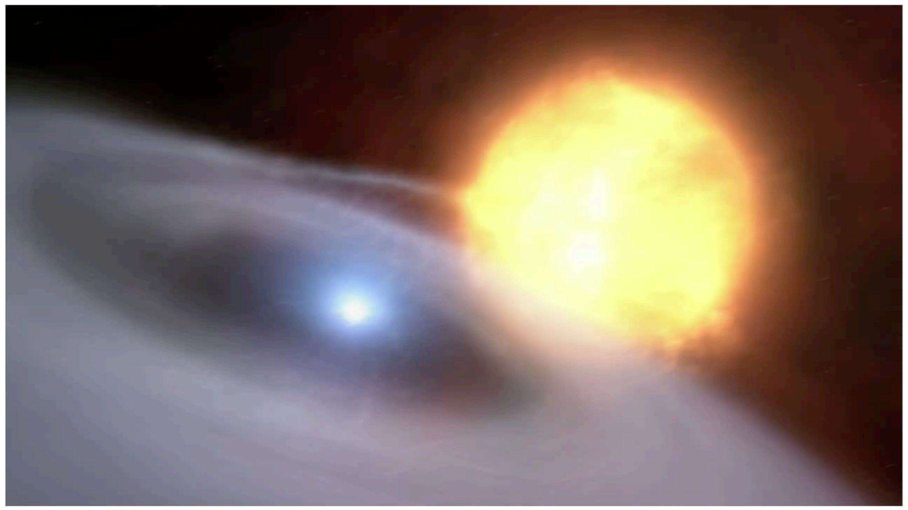
Late-time observations suggest sub-Chandrasekhar mass explosions



- SNe Ia more consistent with sub-Chandrasekhar mass models
- HST + JWST studies to study Ni/Fe ratios

How do Type Ia supernovae explode?

Scenario 1



Explosion at

~$M_{chandra}$ (1.4 Msun)

- Early bumps in 20% (e.g. Deckers+ 2022)
- CSM interaction in 20%

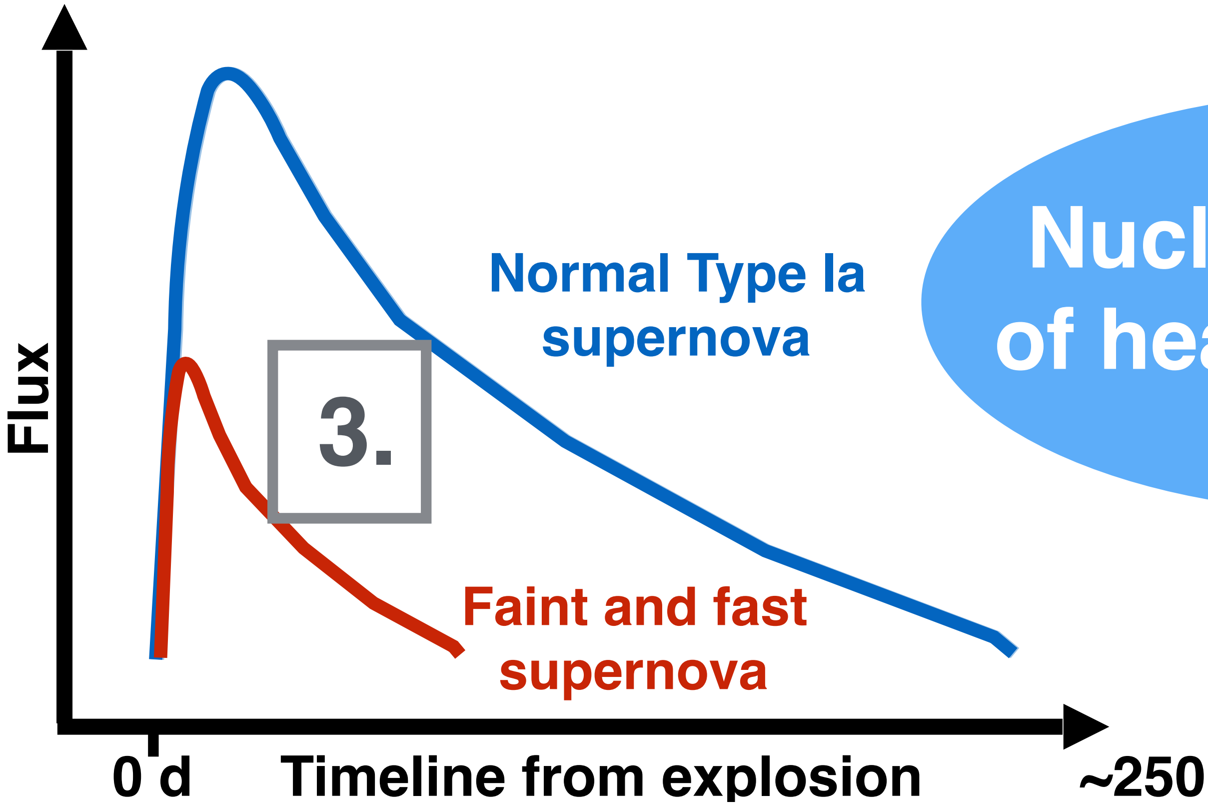
Scenario 2

Explosion

sub-$M_{chandra}$ (<1.4 Msun)

- Ni/Fe ratio at late times
- Lack of companion star detections

- Combined observations from early to late times
- More detailed explosion model predictions



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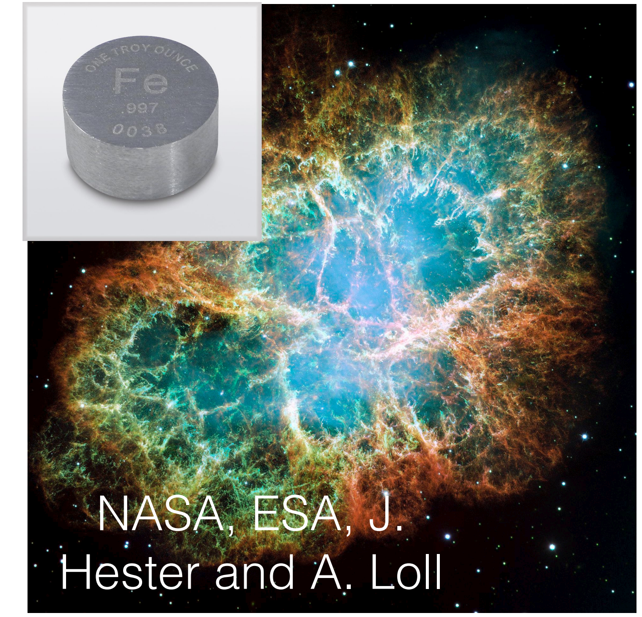
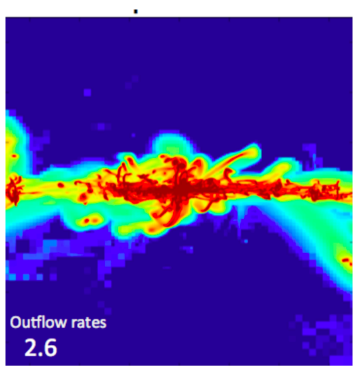


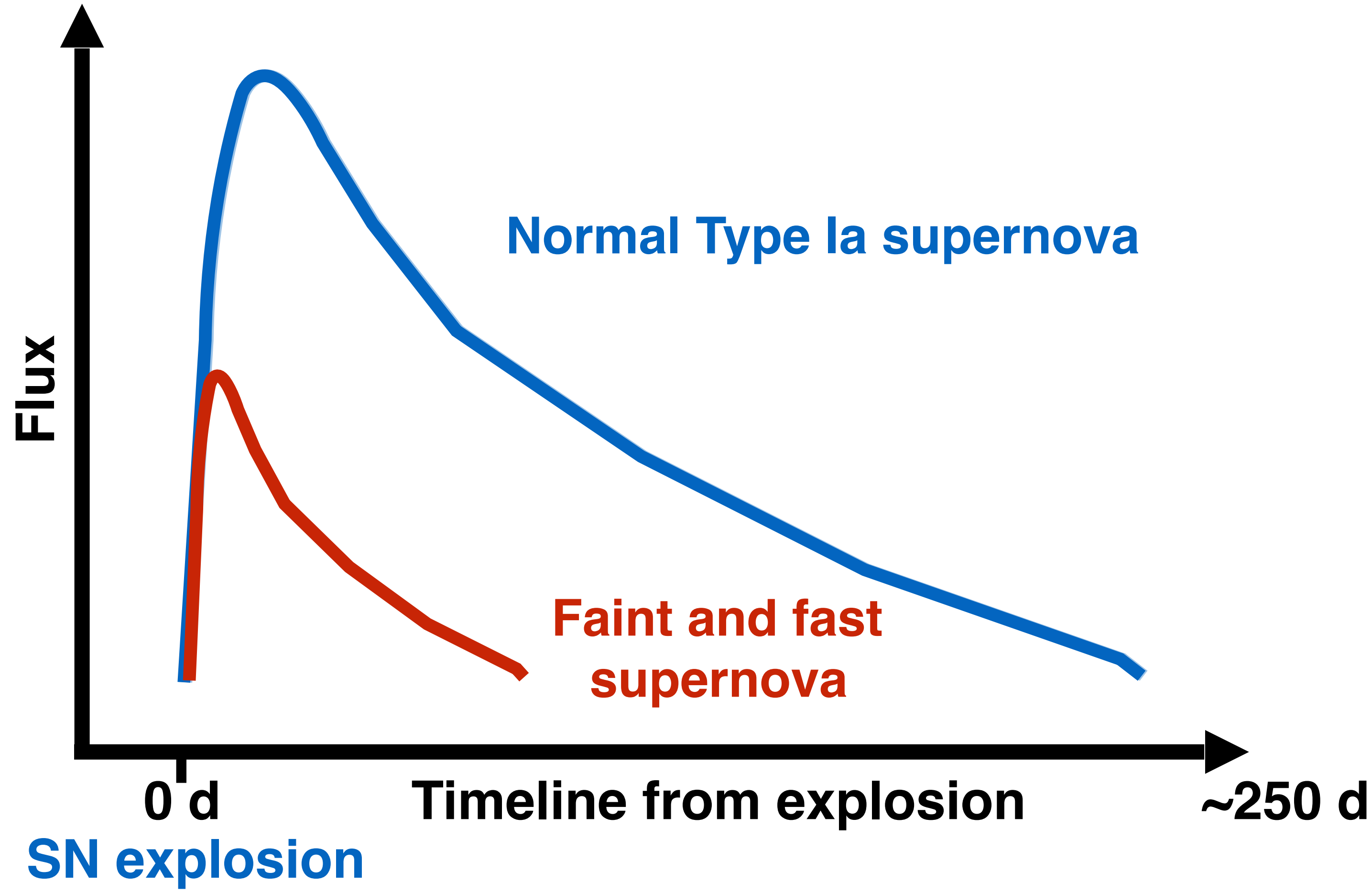


Impact of white dwarf explosions in the Universe

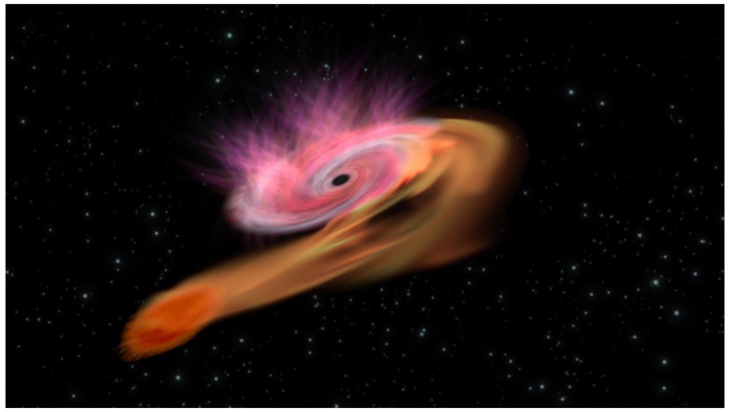
Powering feedback dynamics

Cosmological constraints

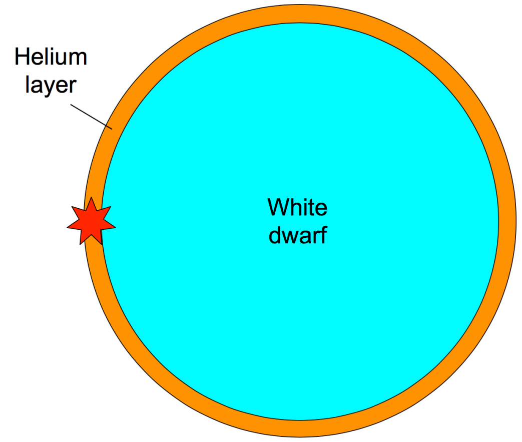
Exploring the unknown: faint and fast white dwarf supernovae



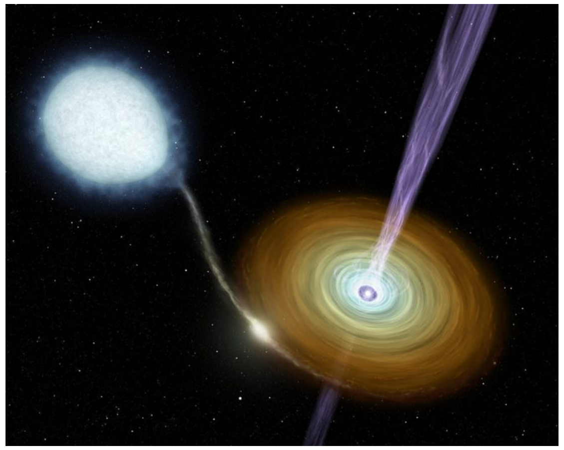
Disruption of a WD by a black hole? (Rosswog+ 2009)



Helium shell detonations? (Shen+ 2010)



White dwarf - neutron star merger? (Metzger 2012)



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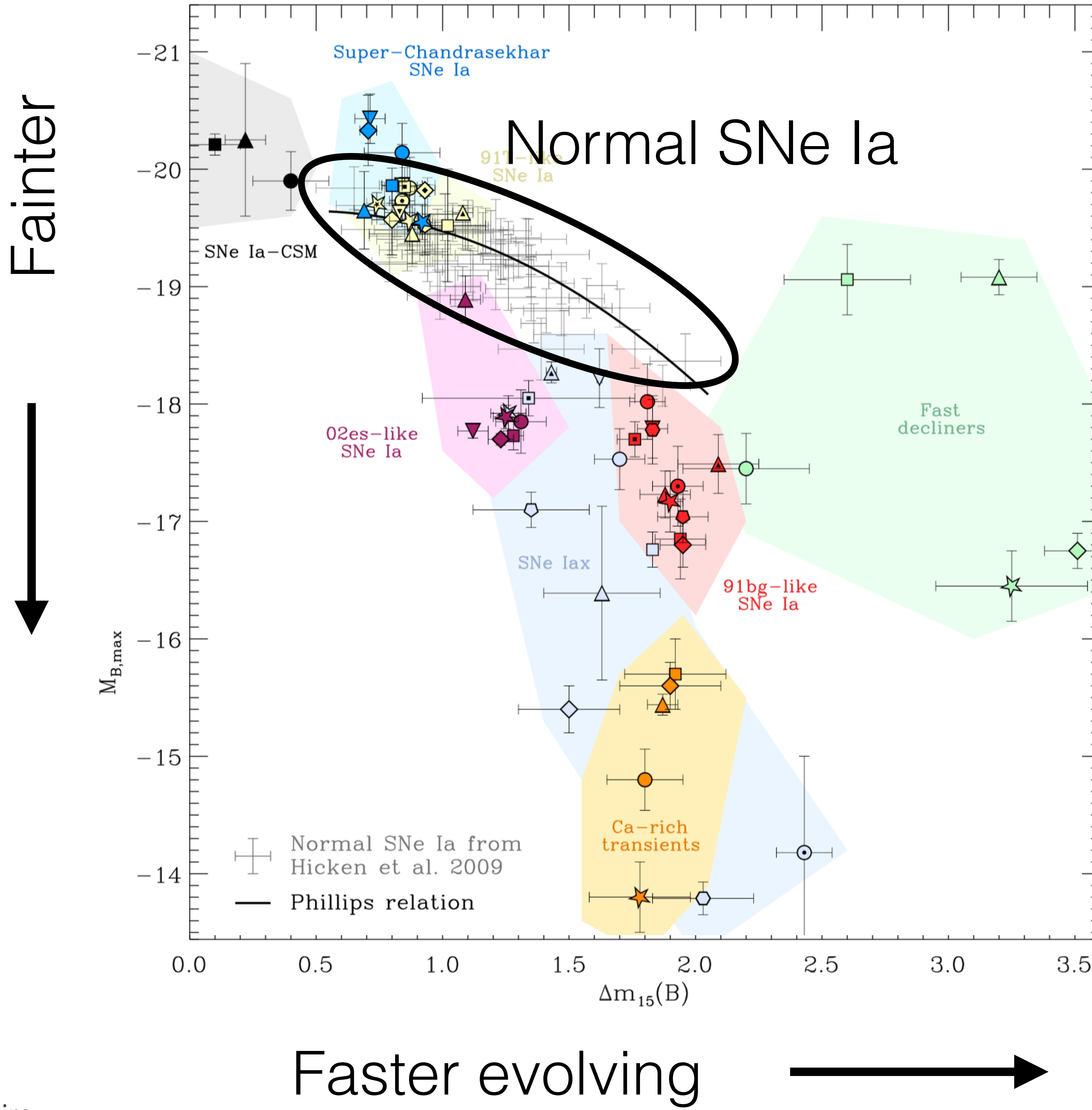
Diversity of white dwarf transients



Taubenberger (2017)

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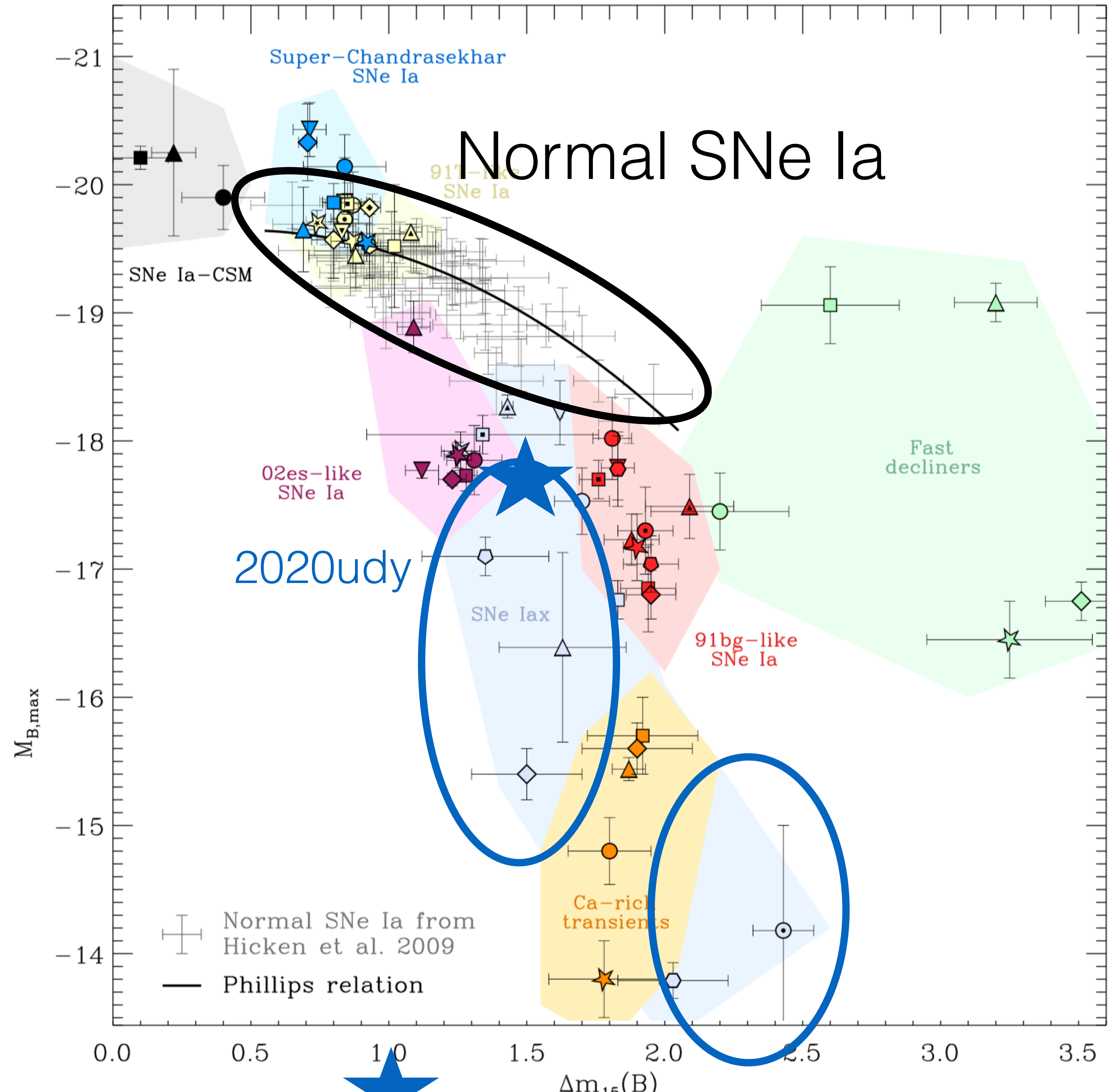
Diversity of white dwarf transients

Fainter



02cx-like or SNe Iax

2021fcg

Faster evolving

Taubenberger (2017)

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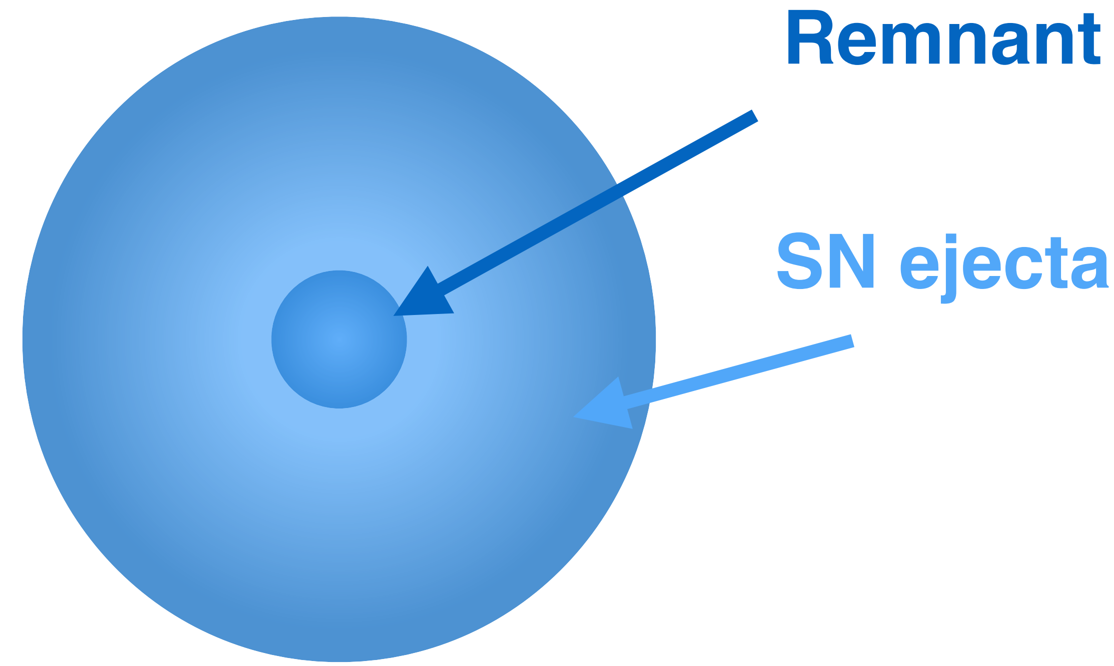
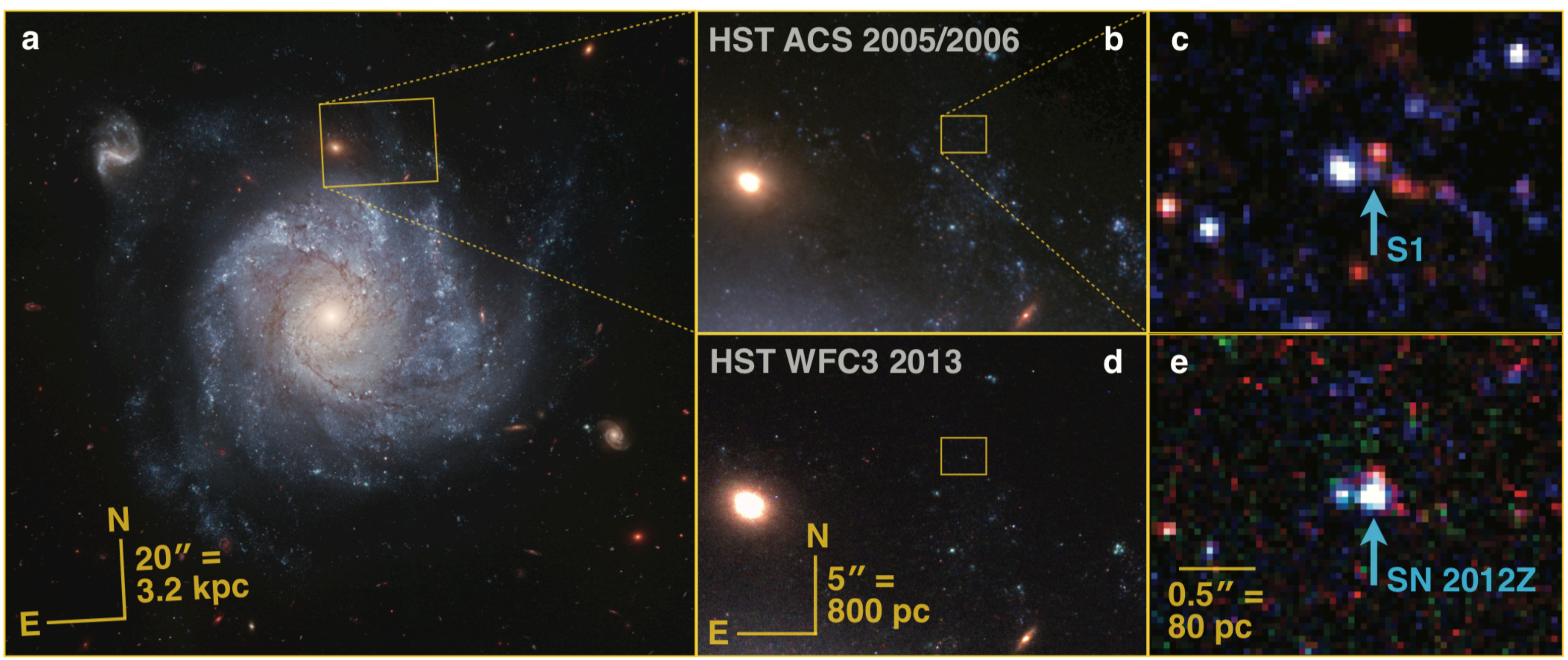
Proposed explosion mechanism for brighter SNe Iax

- Explosion doesn't completely unbind a Chandrasekhar-mass white dwarf (e.g. Fink+ 2014)
- Remnant left behind (~0.2 Msun)
- Pre-explosion imaging suggests blue companion star - He star?

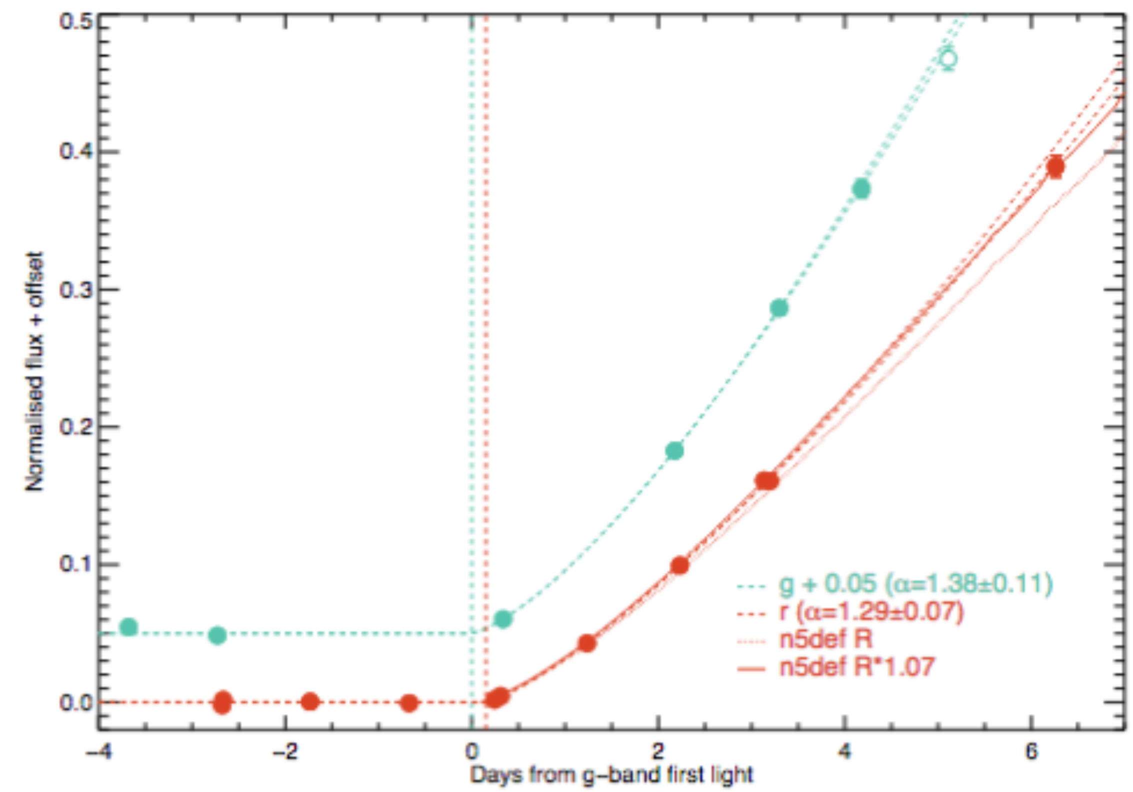


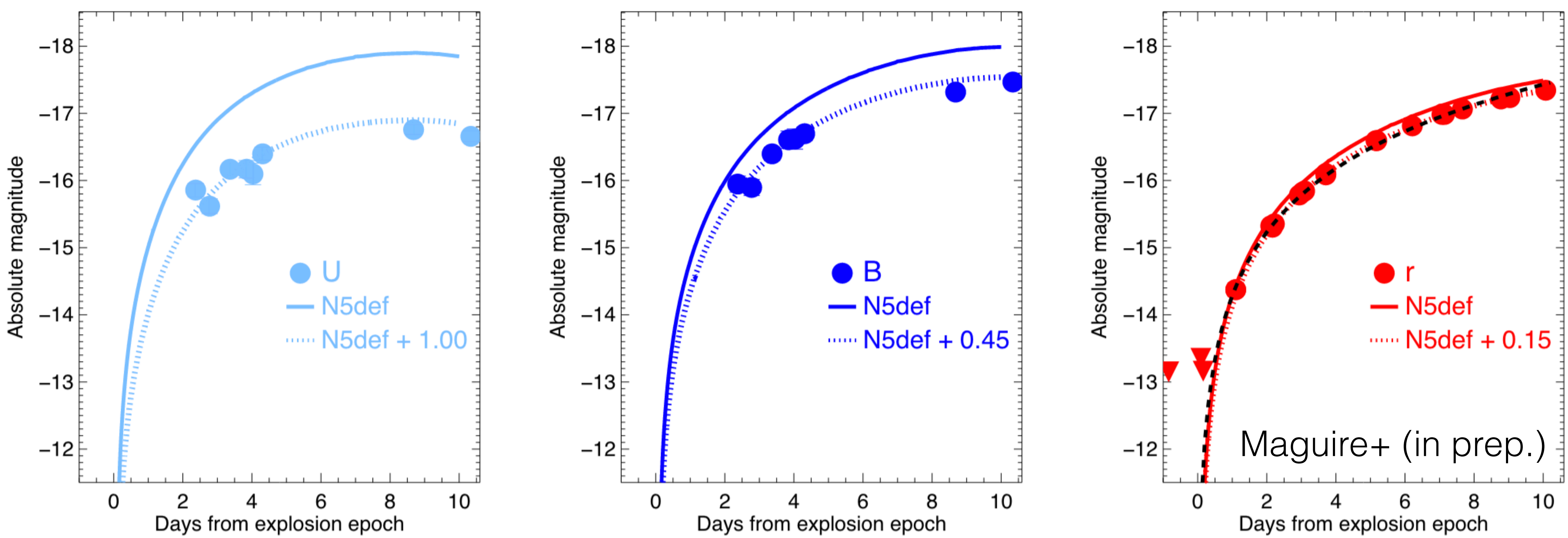


McCully et al. (2014)

SN 2020udy - a bright ZTF-discovered Iax

- Very early detection - 7 hours after expected first light
- Excellent agreement with Mch deflagration model - most consistent with He-star companion
- No polarisation signature





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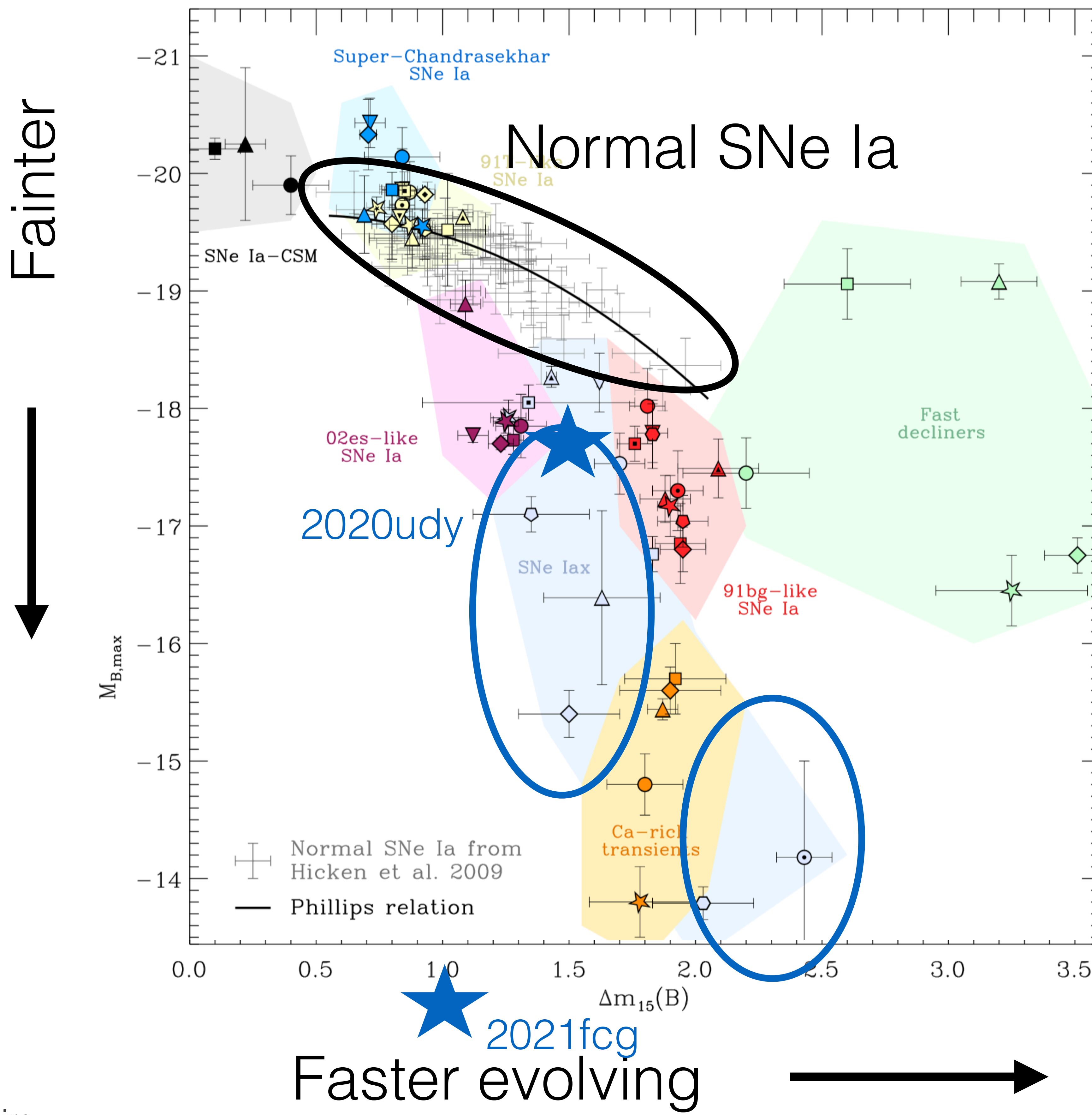

Taubenberger (2017)

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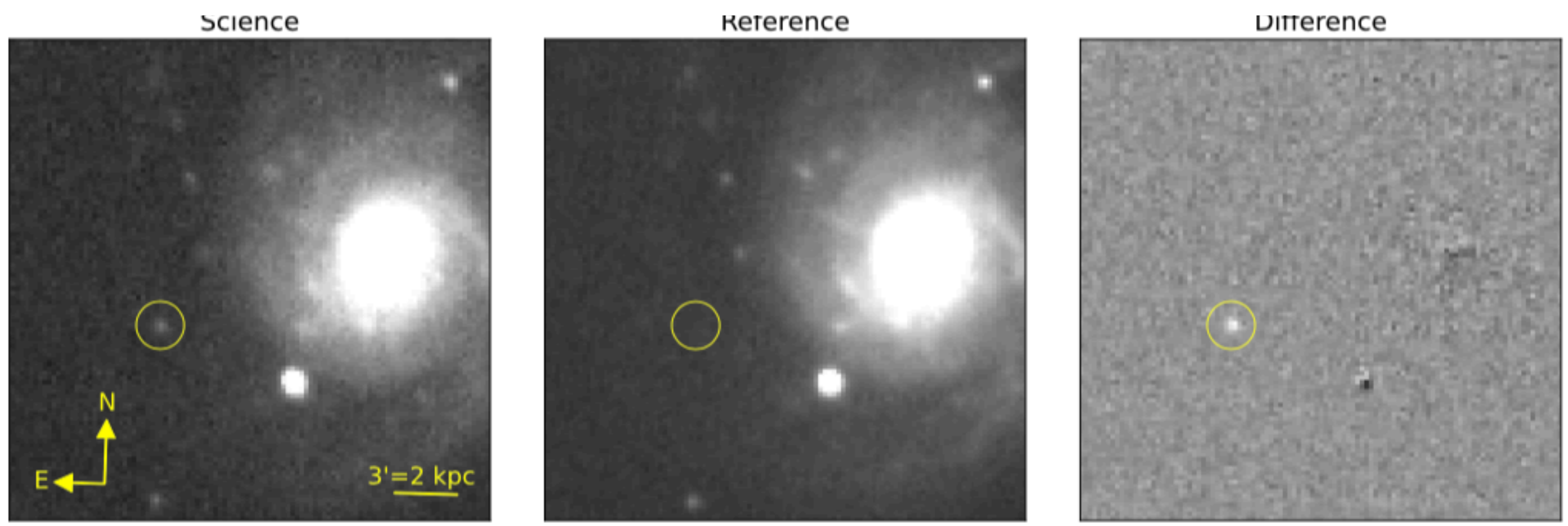
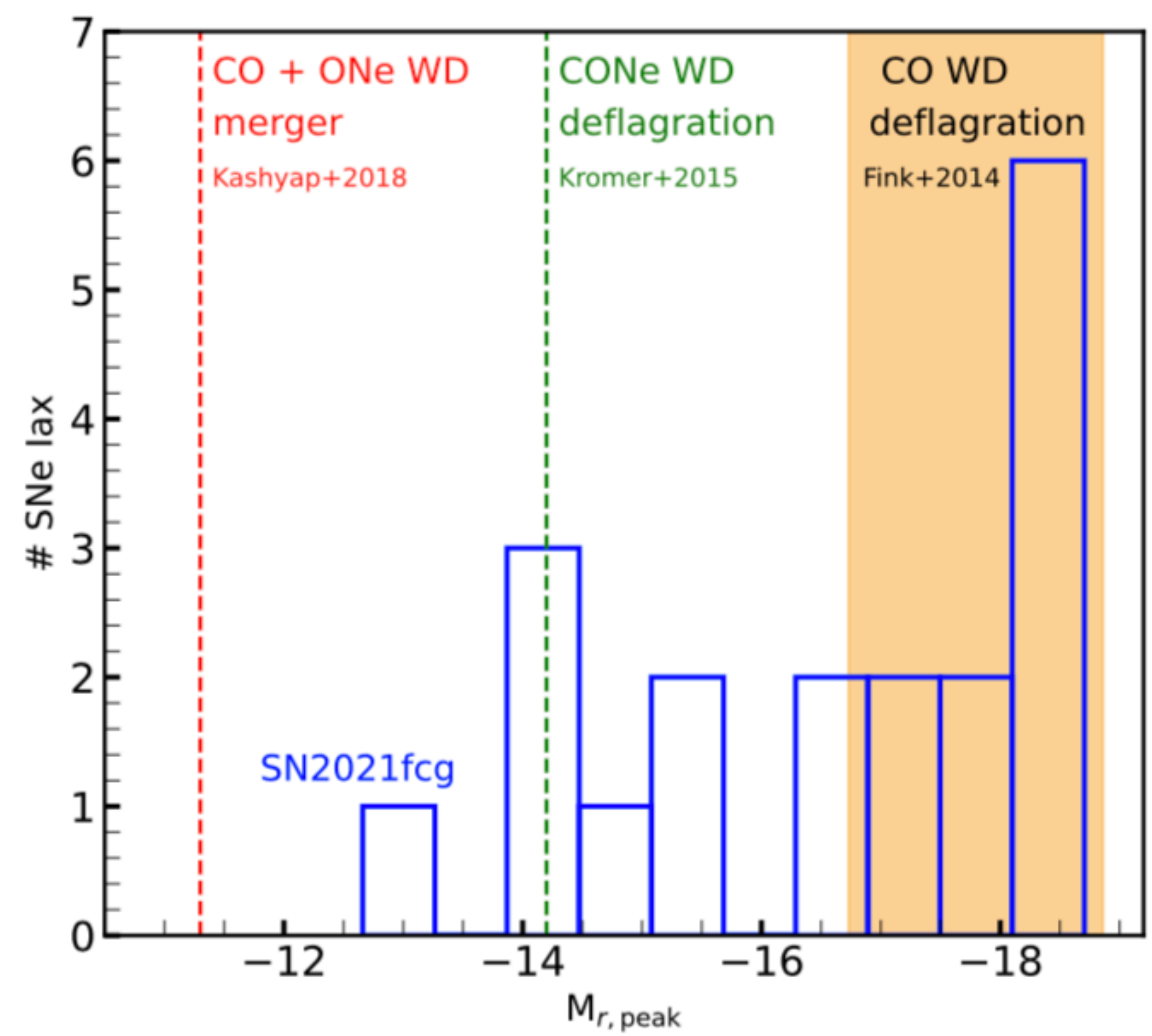
Faintest of them all : ZTF 21aaoryiz/SN 2021fcg – Discovery of an extremely low luminosity Type Iax supernova

Viraj R. Karambelkar,[1] Mansi M. Kasliwal,[1] Kate Maguire,[2] Shreya G. Anand,[1] Igor Andreoni,[1] Kishalay De,[1] Andrew Drake,[1] Dmitry A. Duev,[3] Matthew J. Graham,[1] Erik C. Kool,[4] Russ R. Laher,[5] Mark R. Magee,[2] Ashish A. Mahabal,[6,7] Michael S. Medford,[8,9] Daniel Perley,[10] Mickael Rigault,[11] Ben Rusholme,[5] Steve Schulze,[12] Yashvi Sharma,[1] Jesper Sollerman,[13] Anastasios Tzanidakis,[1] Richard Walters,[14] and Yuhan Yao[1]

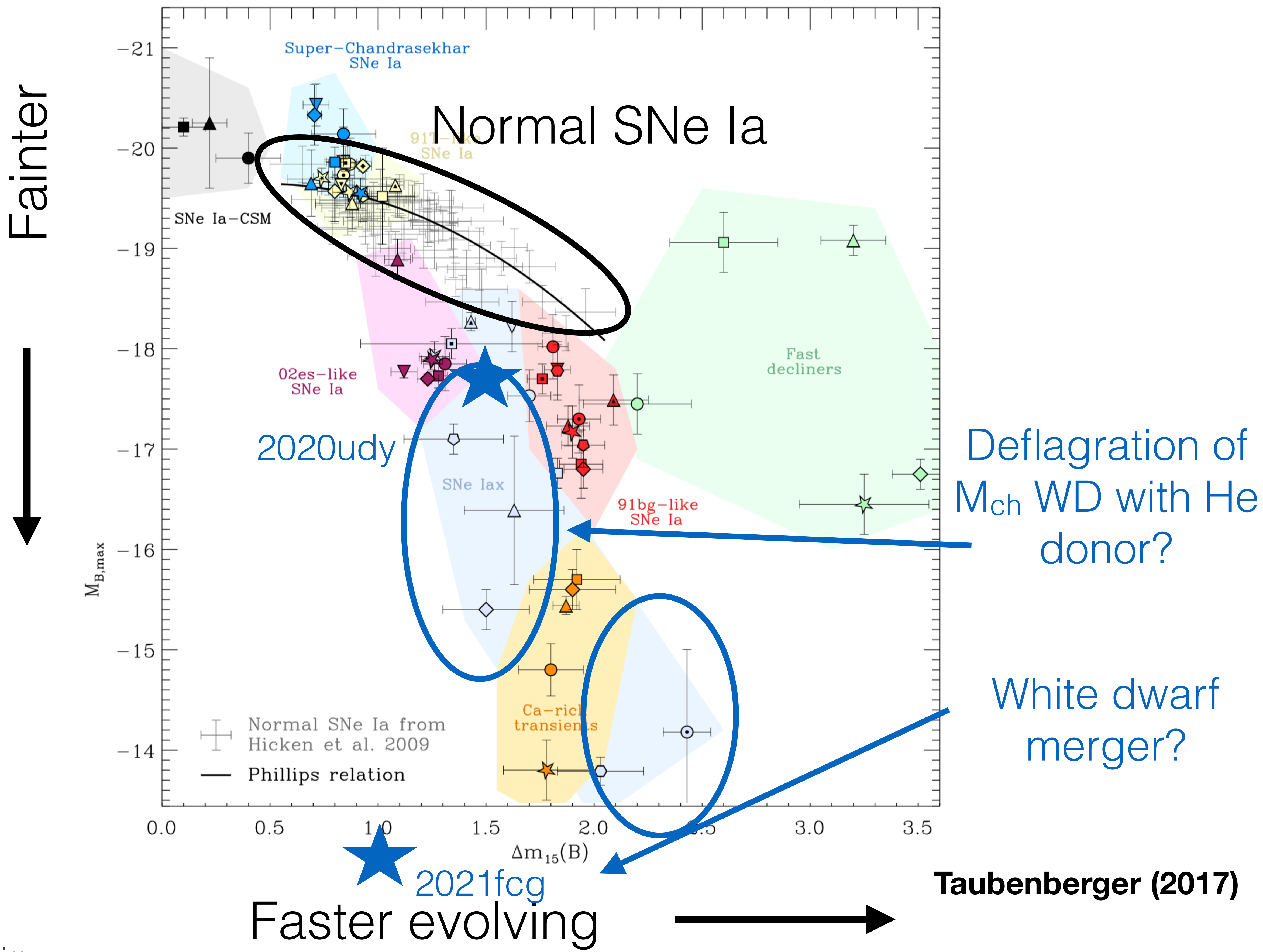


Karambelkar+ (2021)

- Peak of -12.7 mag in r band
- Ni mass of 0.8 x 10^{-3} Msun
- Hybrid CONe WD model deflagration?
- CO + ONe WD Merger?



Diversity of white dwarf transients



Taubenberger (2017)

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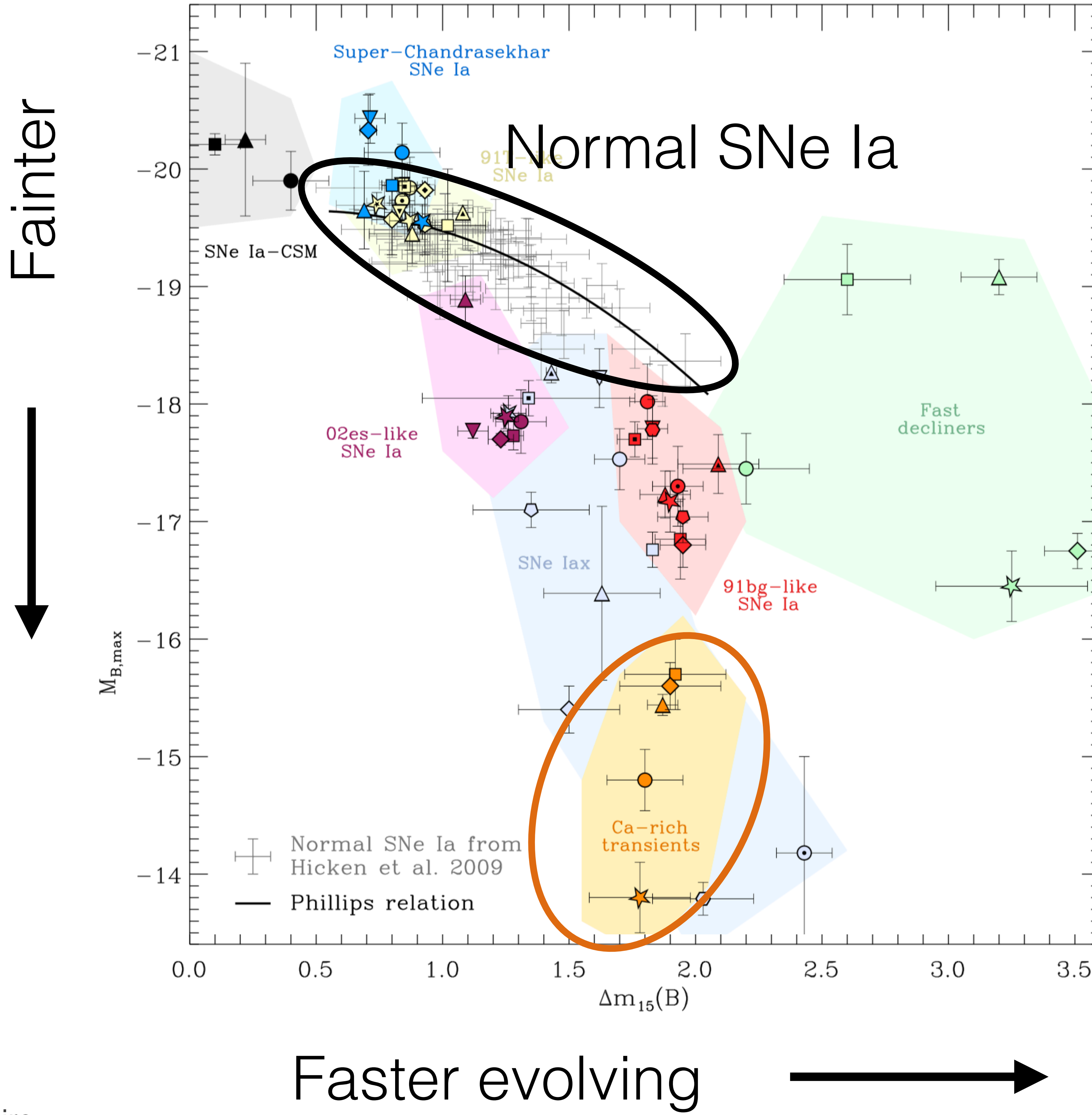
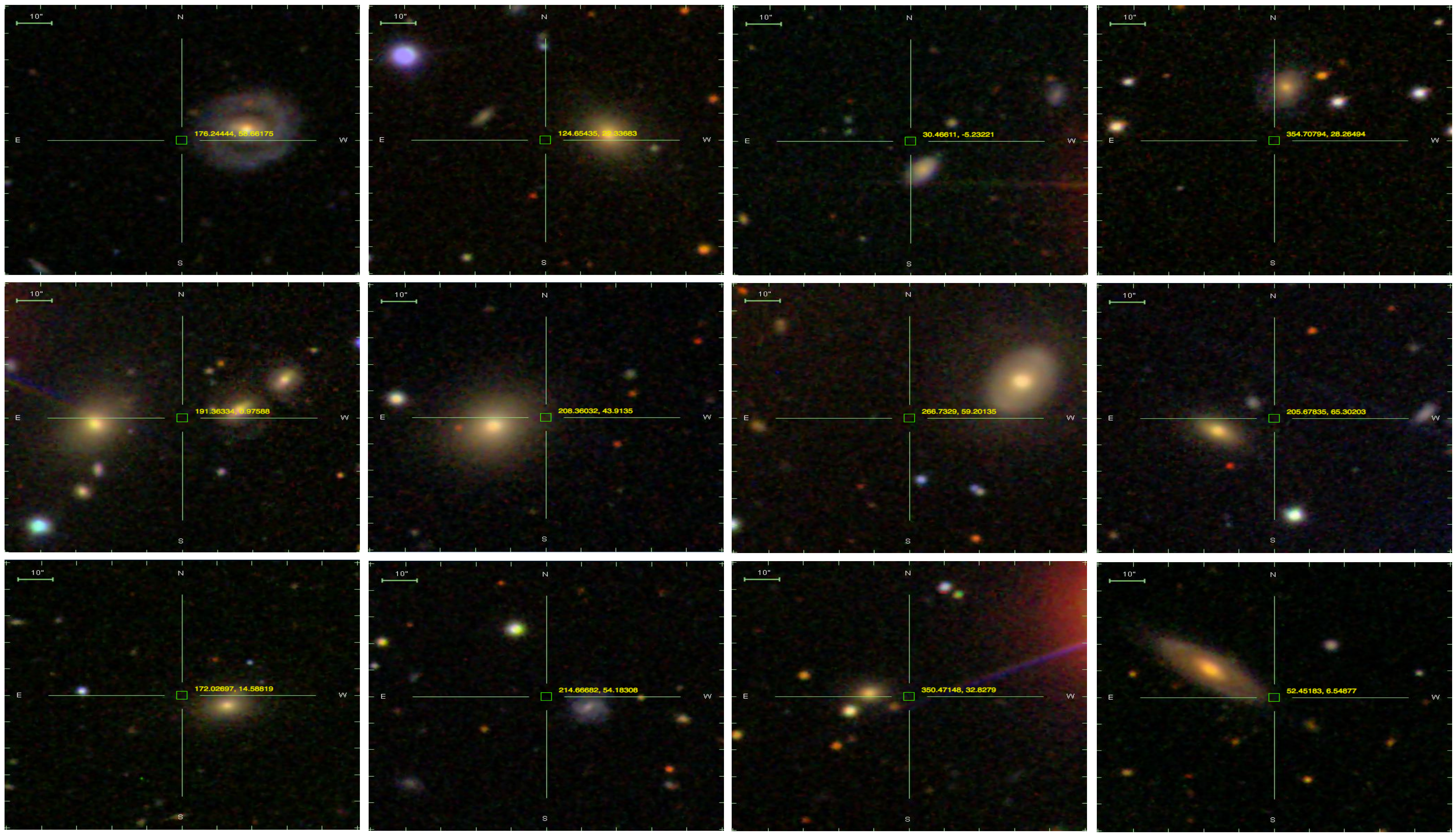


Ca-rich transients

Taubenberger (2017)

Dr. Kate Maguire

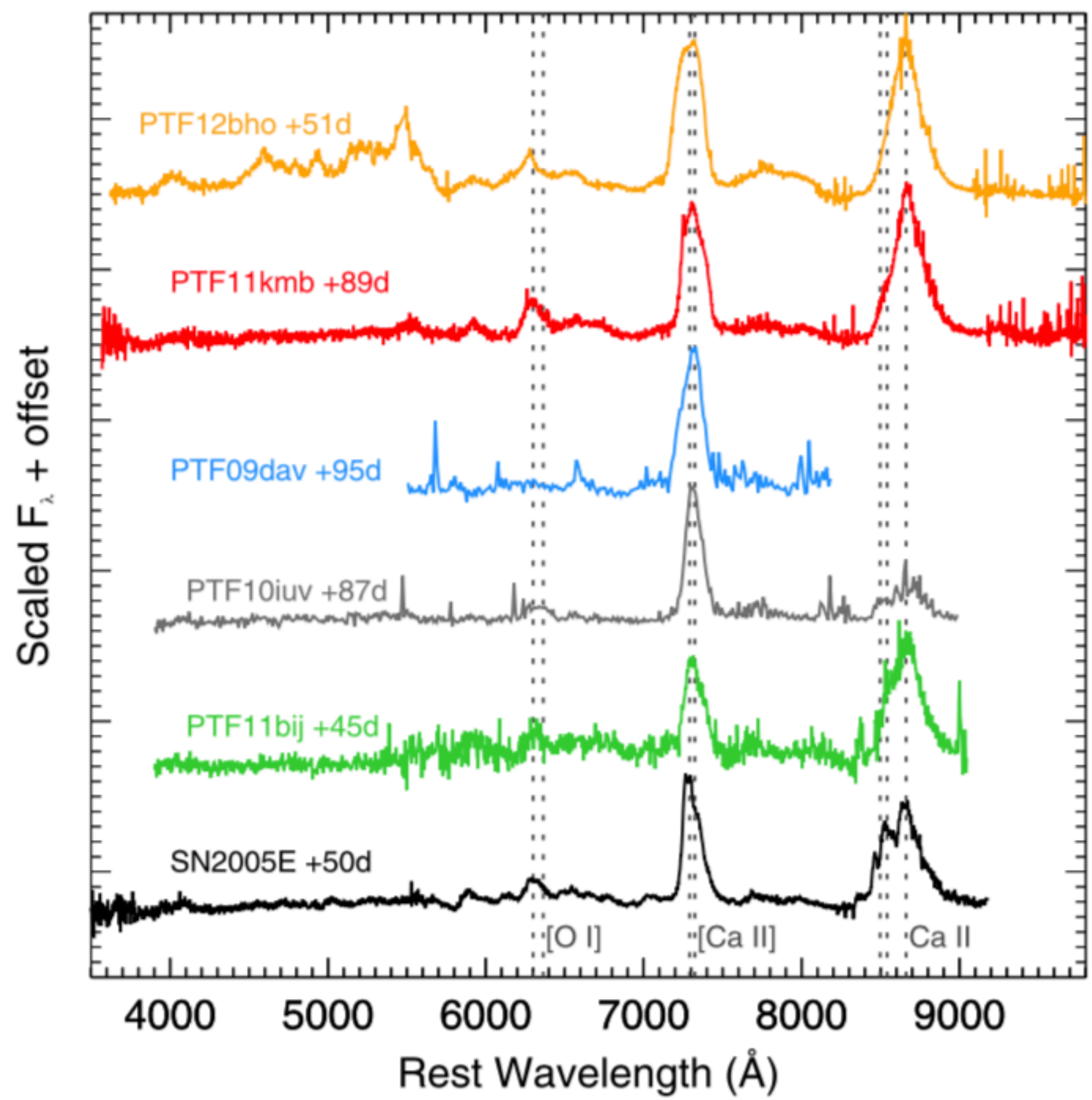
Ca-strong transients - only found in all-sky surveys



- Far from host centre 8 - 80 kpc with some strict limits on globular clusters (Lyman et al. 2016)
- Intrinsic preference for remote locations (Yuan et al. 2013, Frohmaier et al. 2018)

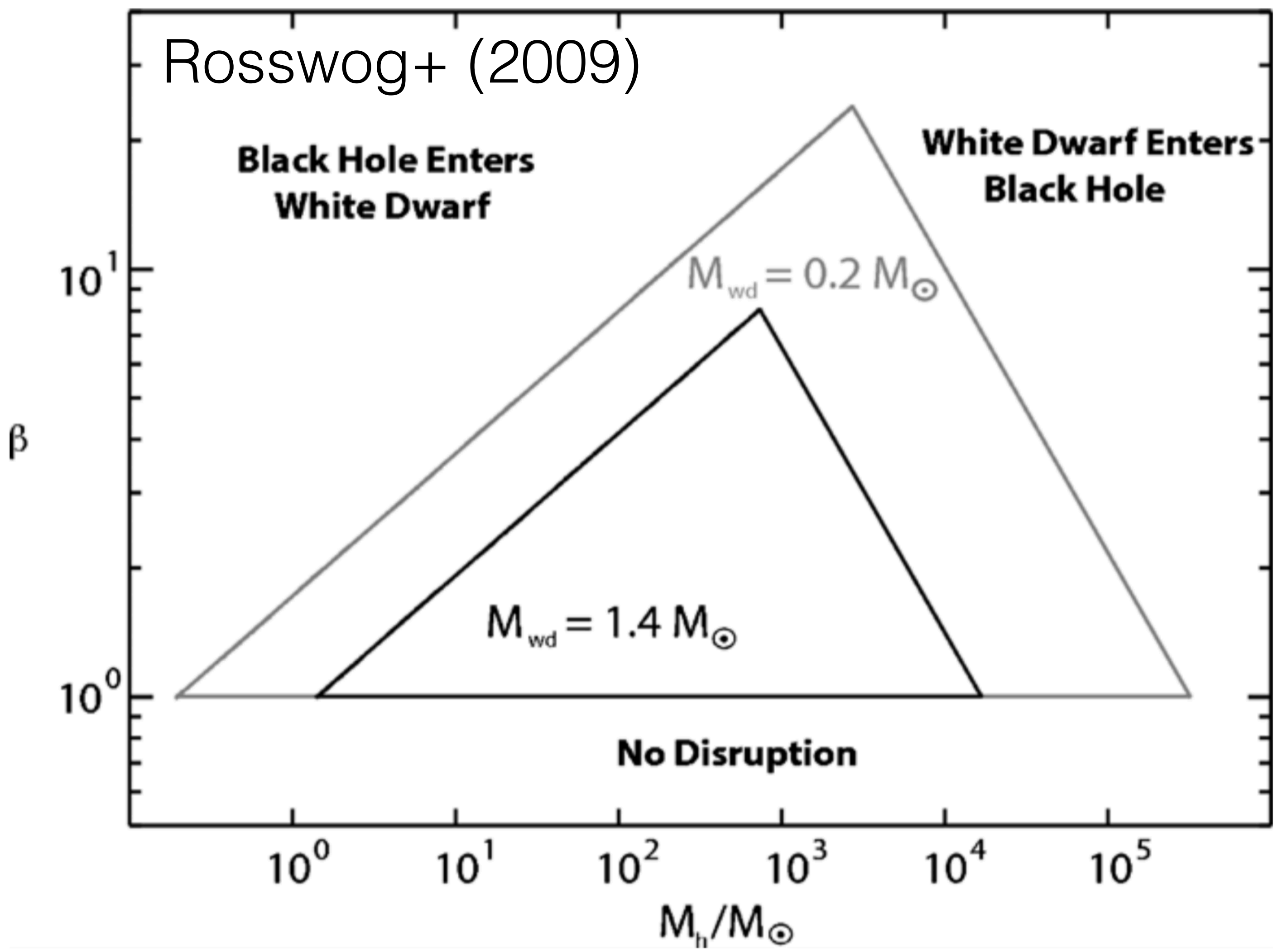
Ca-strong transients - faint and fast evolving

- Strong [Ca II] emission at late times
- 33 - 94% of SNe Ia rate (Frohmaier, Sullivan, KM+ 2018)
- Major contributor to Ca enrichment in the Universe?
- Explanation for observed Ca/Fe over-abundance (de Plaa+ 2007, Mernier+ Mulchaey+ 2014, Mernier+ 2016)?
- He-shell detonations?
- Sell+ (2015) - WD+IMBH TDEs?

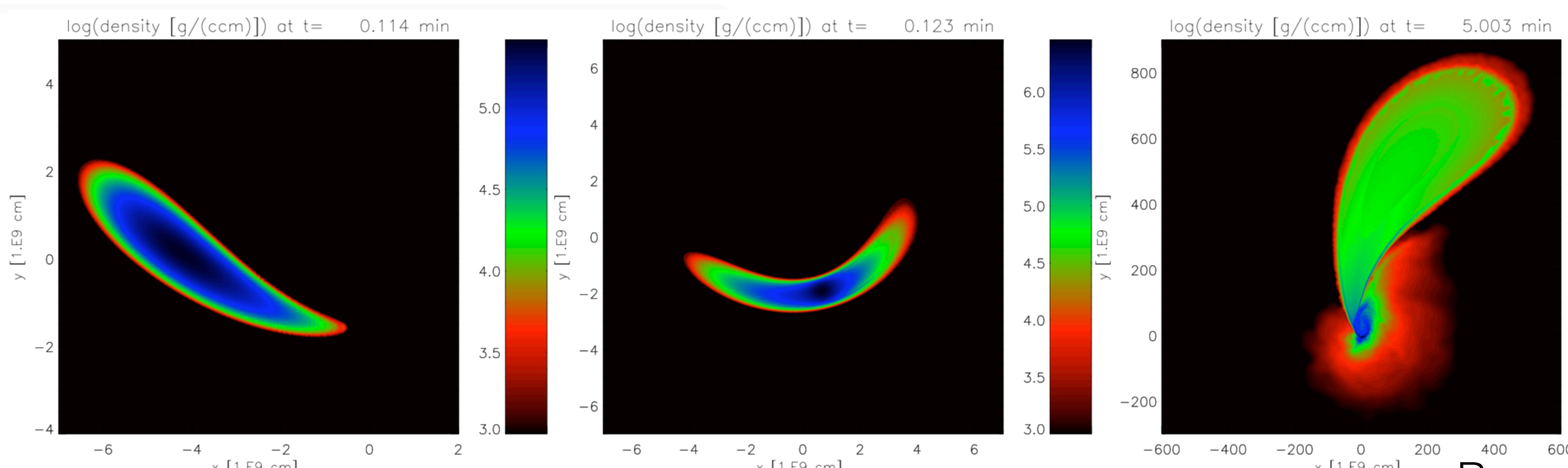


Lunnan et al. (2017)

Tidal disruptions of WD by intermediate-mass black holes

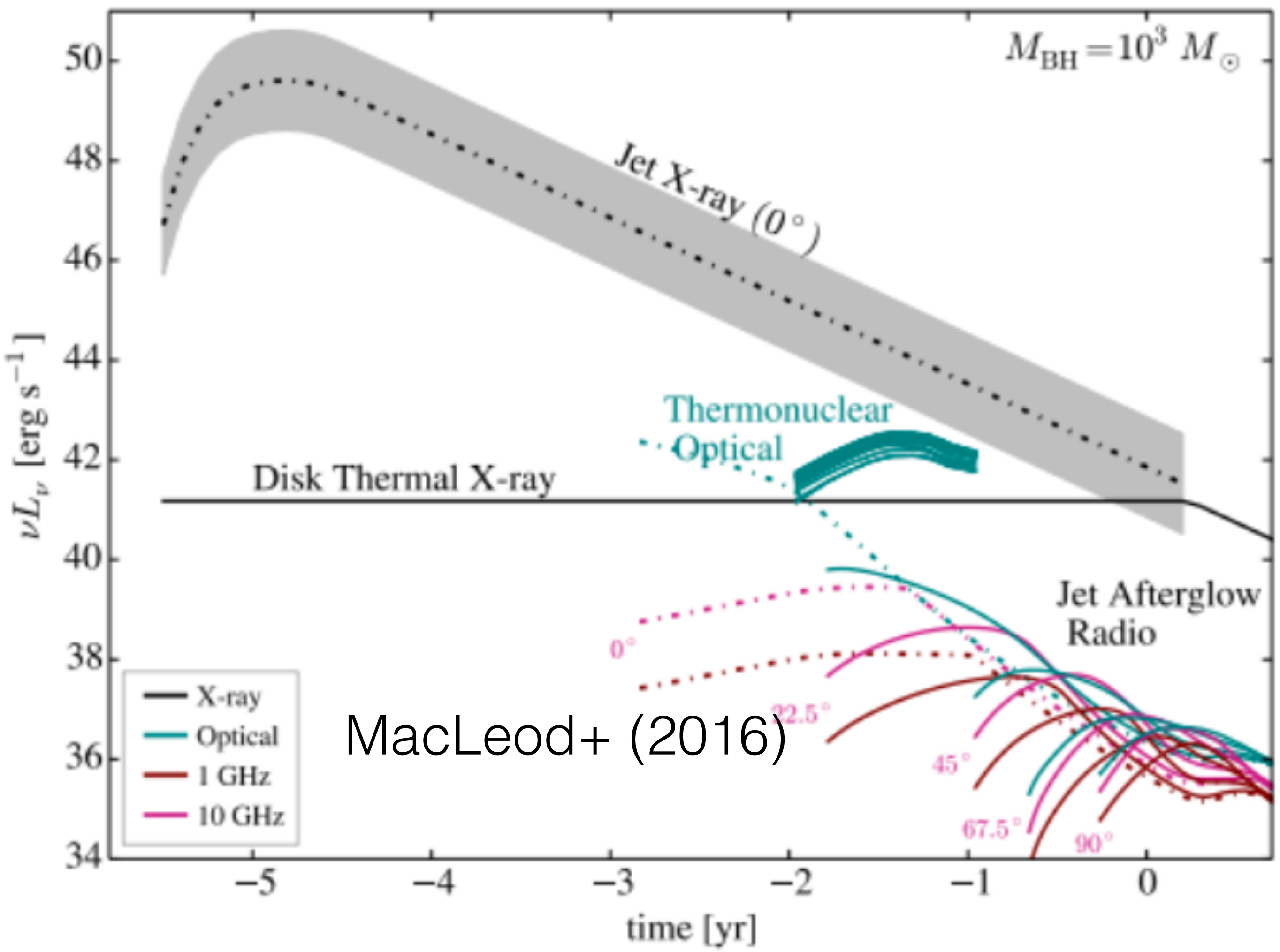


- Simulations of WD+IMBH systems (e.g. Luminet & Pichon 1989; Rosswog+ 2009; Haas+ 2012; Tanikawa+ 2017; Kawana+ 2018; Anninos+ 2018, Tanikawa+ 2018)
-



Rosswog

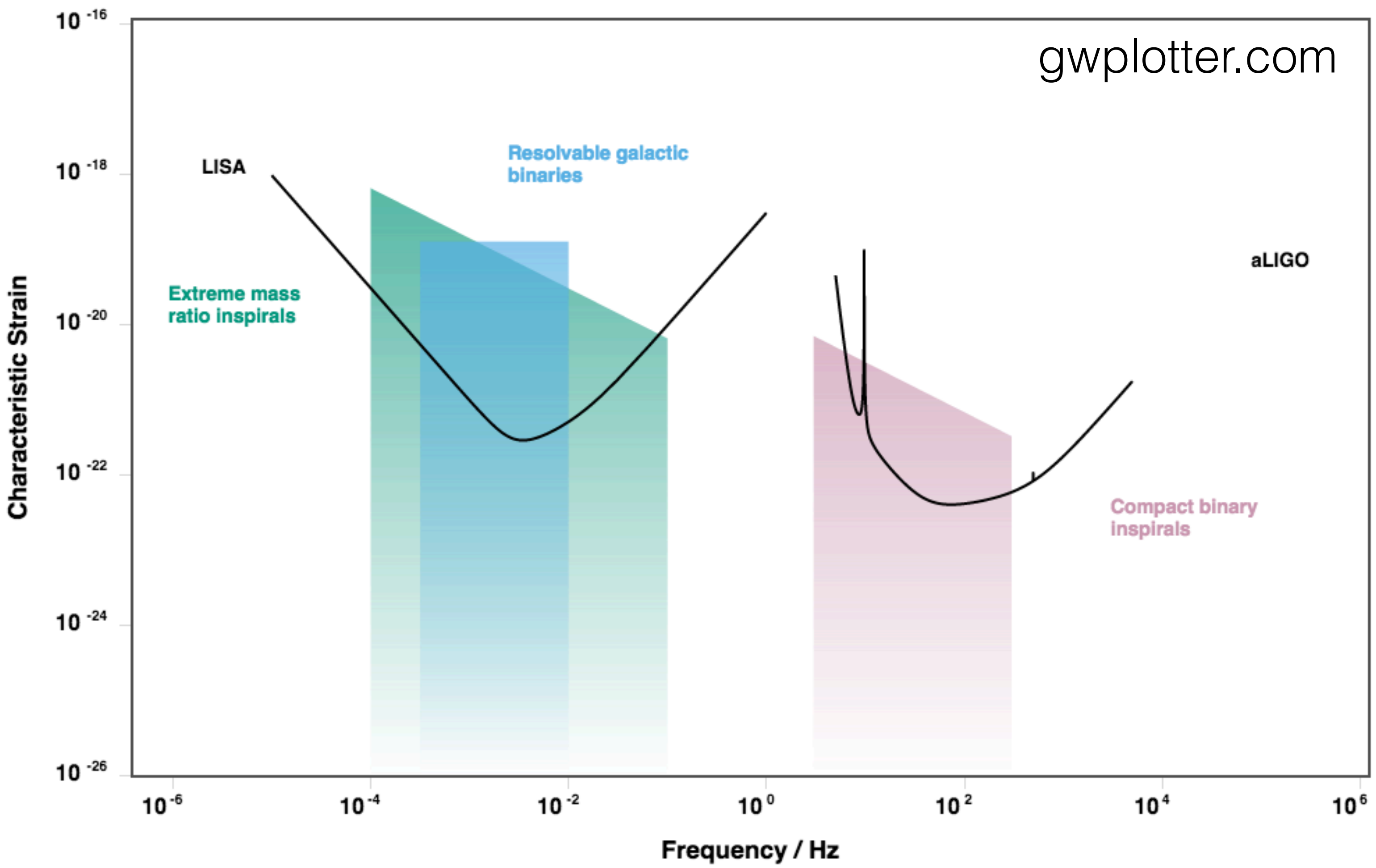
WD TDE observables



- Fall-back accretion, X-ray flare peaking at 0.25 keV (MacLeod+ 2016)
- Light curves of optical transients fainter than normal SNe Ia with wide range of widths depending on viewing angle
- AT2016hnk - Ca-rich with no Chandra X-ray emission (Sell+ 2018)

- Unexplained X-ray flares identified (e.g. Jonker+ 2013, Glennie+ 2015, Bauer+ 2017)
- LSST-detectable event rate of ~ 14 - 290 yr^{-1} (MacLeod+ 2016)
- Connection to other (rarer) exotic transients?

Gravitational wave emission from white dwarfs



- **1) Resolved galactic binaries**
- Measure rates of close white dwarfs and interacting systems
- Probe SN Ia progenitor channels

- Calculations for WD + IMBH TDE - WD on unbound orbit unlikely to be seen in GW
- In bound orbits get **2) 'extreme mass ratio inspirals'**
    - Models for systems up to 100 Mpc (Sesana+ 2008) - build-up of signal during last years of inspiral
- Rare events but get early warning of impending EM TDE

Summary

- **What time-domain/multi-wavelength observations are critical for answering fundamental science questions for this source?**
  - **Cosmology** - coordinated space (high-z) and ground (low-z/mid-z) observations
  - **SN Ia progenitors, physics, & nucleosynthesis** - ground-based high cadence survey, UV + NIR, low-frequency GW
  - **Diversity of WD explosions** - high cadence ground-based observations, coordinated X-ray, UV & optical, low-frequency GW
- **Is this source a potential multi-messenger candidate (i.e., expected to be detected in GW and/or particles/neutrinos)? If so, what is the expected multimessenger output and the prospects for detection in the next 10 years?**
  - TDEs from WD+IMBH - low-frequency GW
- **What is needed for the time domain/multi-wavelength and/or multi-messenger detections described above (more theory work, more observations, new technology, new missions/facilities, etc.)?**
  - Theory work on explosion models, coordinated observations, UV, low-frequency GW